İSTANBUL TECHNICAL UNIVERSITY ★ INSTITUTE OF SCIENCE AND TECHNOLOGY

PERFORMANCE EVALUATION OF IEEE 802.16e STANDARD

MSc. Thesis by
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ABREVIATIONS AND ACRONYMS

AAS	: Adaptive Antenna System
AMC	: Adaptive Modulation and Coding
AMS	: Adaptive MIMO switching
ARQ	: Automatic Repeat Request
BE	: Best Effort
BER	: Bit Error Ratio
BPSK	: Binary Phase Shift Keying
BS	: Base Station
BW	: Bandwidth
BWA	: Broadband Wireless Access
CC	: Convolution Code
CDMA	: Code Division Multiple Access
CPS	: Common Part Layer
CPE	: Costumer Premise Equipment
CQI	: Channel Quality Indicator
CRC	: Cyclic Redundancy Code
ECC	: Error Correction Code
ErtPS	: Extended real-time Polling Service
ETSI	: European Telecommunication Standards Institute
FBSS	: Fast Base Station Switching
FDD	: Frequency Division Duplex
FEC	: Forward Error Correction
FFT	: Fast Fourier Transform
FUSC	: Full Usage of Sub-Channels
HARQ	: Hybrid Automatic Repeat Request
HHO	: Hard Handoff
IEEE	: Institute of Electrical and Electronics Engineers
ISI	: Inter-Symbol Interference
LAN	: Local Access Network
LLC	: Logical Link Control
LOS	: Line Of Sight
MAC	: Medium Access Control
MAP	: Media Access Protocol
MDHO	: Macro Diversity Hand Over
MIMO	: Multiple Input Multiple Output
MS	: Mobile Station
NF	: Noise Figure
nrtPS	: non-real-time Polling Service
OFDM	: Orthogonal Frequency Division Multiplex
OFDMA	: Orthogonal Frequency Division Multiple Access
PDU	: Packet Data Unit

PHY	: Physical Layer Protocol
PL	: Path Loss
PMP	: Point to MultiPoint
PUSC	: Partially Used Sub-Carriers
PTP	: Point to Point
QAM	: Quadrature Amplitude Modulation
QPSK	: Quadrature Phase Sift Keying
RTG	: Receive/transmit Transition Gap
rtPS	: real-time Polling Service
SC	: Single Carrier
SDU	: Service Data Unit
SNR	: Signal Noise Ratio
SS	: Subscriber Station
SUI	: Standford University Interim
TCP	: Transmission Control Protocol
TDD	: Time Division Duplex
TTG	: Transmit/receive Transition Gap
TTI	: Transmission Time Interval
UGS	: Unsolicited Grant Service
VoIP	: Voice over IP
WiMAX	: Worldwide Interoperability for Microwave Access
WLAN	: Wireless Local Area Network

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ÖZET

Bu çalışma Mobil WiMAX ‘te kapsama alanını ve veri hızı hakkındaki çalışmaları içerir. Tez WiMAX hakkında genel bilgi, gelişimi ve tanımları vererek başlıyor. Okuyucu WiMAX hakkında ve faydaları hakkında tam bir fikre vardığında, Fiziksel Katmanı da, kapsama alanına ve veri hızına etki eden özel nitelikle daha detaylı açıklanacak. Bu nokta Mobil ve Sabit WiMAX Fiziksel Katları arasında karşılaştırma ile bitecektir.

Daha detaylı hesaplamalar için diğer görüşler belirtilip çalışılmıştır. Bu grupta 802.16e-2005 Standardının özel parametreleri, mevcut donanım parametreleri, frekans kullanım planı ve muhtemel yayılım modelleri bulunmaktadır.

Gerekli tüm bilginin açıklanmasından sonra hesaplamalar çok kolay bir şekilde anlaşılacaktır. Bunlar teorik kapsama alanı yarıçapı ve her bir kapsama alanı için elde edilen maksimum veri hızıdır.

Sonuçtan önce WiMAX ‘in ne olduğu hakkında daha iyi bir genel düşünce sağlaması açısından İstanbul çevresinden bazı ölçümler elde edilmiştir. Bir Sabit WiMAX Baz İstasyonu Elektrik Elektronik Fakültesine yerleştirilmiştir, Mobil WiMAX ‘e göre birçok farklı özellikler ile çalışır ve hala ilgi çekicidir.

SUMMARY

This paper consists in a research of coverage and data rate for Mobile WiMAX. The thesis commences with a general introduction about WiMAX, evolution and general overview. Once the lector has obtained a complete idea of WiMAX and its benefits, the Physical Layer will be further explained with special attention on attributes which affect the coverage and the maximum data rate. This point is finished with a short comparison between Mobile and Fixed WiMAX Physical Layers.

In order to achieve rigorous calculations, other aspects have been studied and described. In this group it can be found: specific parameters of 802.16e-2005 Standard, current equipment parameters, frequency usage plan and possible propagation models.

After the explanation of all required information, the calculations can be easily realized. Thus, theoretical coverage radius and maximum data rate for each coverage area are obtained.

Before conclusions in order to provide a better concept about what WiMAX is, some measurements have been taken in Istanbul. A Fixed WiMAX Base Station is located in Electrical Faculty, which works with many different features comparing with Mobile WiMAX but it is still interesting.

1. INTRODUCTION

In the last ten years Wireless Network usage and development has been established in the society firmly. Due to this sharp progress and investment, it has been necessary to found a single Standard for each Wireless Network. These Standards are developed by the IEEE organization (Institute of Electrical and Electronics Engineers) placed in United States.

The widest Wireless Standard is IEEE 802.11, well known as WiFi. The first release of this Standard was finished in 1999 (ANSI/IEEE Std 802.11 1999 Edition) but afterwards there has been successive Specifications as 802.11a, 802.11b and 802.11g where alterations are located mainly in the physical layer, remaining basically the same MAC layer since the original Specification.

During the development of the IEEE 802.11 Standard, a new Wireless Network idea emerged, instead of being developed for a Local Area Network it is patterned for Metropolitan Area Network. It means, for a whole city. This Standard was defined as IEEE 802.16 and it was developed in order to fill the gap between 802.11 LAN IP-based network and GSM. The new Standard will achieve high bandwidth efficiency (higher than 802.11 or GSM) and in the last amendment it will support mobility, although more restricted than GSM.

The first Specification was approved in 2001 however it has still short integration in the society. This new Standard is commonly named WiMAX since this is the name for the organization responsible of certifying products related with IEEE 802.16.

WiMAX is based on the IEEE 802.16 standard and on ETSI HiperMAN. The next version of IEEE 802.16, 802.16-2004 (previously known as Revision D, or 802.16d), was ratified in July 2004. 802.16-2004 includes previous versions (802.16-2001, 802.16c in 2002, and 802.16a in 2003) and covers both LOS and NLOS applications in the 2-66 GHz frequencies. As is habitual with IEEE standards, it specifies only the Physical (PHY) and Media Access Control (MAC) layers.

The changes introduced in 802.16-2004, respect previous Standards, were focused on fixed and nomadic applications in the 2-11 GHz frequencies. Two multi-carrier modulation techniques are supported in 802.16-2004: OFDM with 256 carriers and OFDMA with 2048 carriers. The first WiMAX Forum certification profiles are based on OFDM as defined in this version of the standard.

In December 2002, Task Group was created to improve support for combined fixed and mobile operation in frequencies below 6 GHz. Work on the 802.16e amendment is already completed. The new version of the standard introduces support for scalable OFDMA (a variation on OFDMA) which allows scalability for a variable number of carriers (at least 512, 1024 and 2048), in addition to the previously-defined OFDM and OFDMA modes. The carrier allocation in OFDMA modes is designed to minimize the effect of the interference on user devices with omnidirectional antenna. Furthermore, IEEE 802.16e offers improved support for Multiple Input Multiple Output (MIMO) and Adaptive Antenna Systems (AAS), as well as hard and soft handoffs. It also has improved power-saving capabilities for mobile devices and more extensive security features. As with 802.16-2004, 802.16e incorporates previous versions of the standard and adds support for fixed and mobile access. The Amendments of Mobile WiMAX respect IEEE 802.16-2004 Standard will be further explained and described in this document.

In the following points of the Introduction, basic concepts of WiMAX are explicated, since otherwise Standard would hardly be understood.

1.1 Frequency Bands

Three different frequency bands are described in WiMAX Standard (both 802.16-2004 [4] and 802.16e-2005 [1]): two Licensed Bands, 10 – 60 GHz for line-of-sight (LOS) and Frequencies below 11 GHz for both near-LOS and non-line-of-sight (NLOS) and on the other hand, the last frequency band is License-exempt and below 11 GHz.

However, there are only certified products for frequencies below 11 GHz, therefore the frequency band 10 – 60 GHz is only described for the theory but not for practice. Then, within this context:

Frequencies below 11 GHz

In the frequencies below 11GHz due to the longer wavelength line-of-sight is no required and multipath may be negligible. For supporting near-LOS and non-line-of-sight (NLOS) scenarios it is required additional PHY functionality. Optionally some MAC features can be introduced, such as Mesh topology and Automatic Repeat Request (ARQ).

This range of frequencies may be licensed or license-exempt bands. They are similar; however license-exempt bands introduce additional interference. The PHY and MAC introduce Dynamic Frequency Selection (DFS) mechanism in order to detect and avoid interference.

License-exempt frequencies below 11 GHz (primarily 5-6 GHz)

The physical environment for the license-exempt bands below 11 GHz is similar to that of the licensed bands in the same frequency range. However, the license-exempt nature introduces additional interference and co-existence issues, whereas regulatory restrictions limit the allowed radiated power. In addition to the characteristics described, the PHY and MAC introduce mechanisms such as dynamic frequency selection (DFS) to facilitate the detection and avoidance of interference and the prevention of harmful interference into other users including specific spectrum users identified by regulation.

In the context of the IEEE 802.16 Standard, the use of the term “license-exempt frequencies” or “license-exempt bands” should be taken to mean the situation where licensing authorities do not coordinate individual assignments to operators, regardless of whether the spectrum in question has a particular regulatory status as license-exempt or licensed.

1.2 Topology and Architecture

When there is a common air medium which must be shared, an efficient sharing mechanism has to be used to utilize it in an efficient way. In the IEEE Standard 802.16 there are two different sharing wireless media; Point to Multipoint (PMP) and Mesh topology wireless networks.

1.2.1 PMP

This topology operates with a central Base Station (BS) and its sectorized antenna which has the capability of handling multiple independent sectors simultaneously. Within a given frequency and antenna sector, when the BS transmits all the Subscriber Stations (SSs) receive the same transmission. The BS owns the control of the downlink. Respect the Uplink, all the transmissions are directed to the BS. The BS manages the network by coordinating the transmission of the SSs. It does not require coordinating its transmission with other stations.

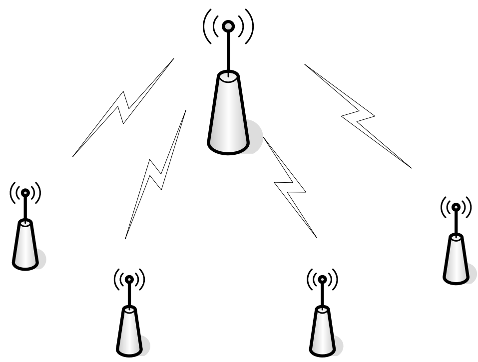

Figure 1.1: PMP Network topology

1.2.2 Mesh

The main difference between the PMP and Mesh mode is related with the link among the stations. In PMP all the transmission occurs between the BS and SSs, whereas in Mesh mode the traffic can be placed directly between two SS and the SSs do not must transmit directly to the BS. The traffic can be enrouted through other SSs.

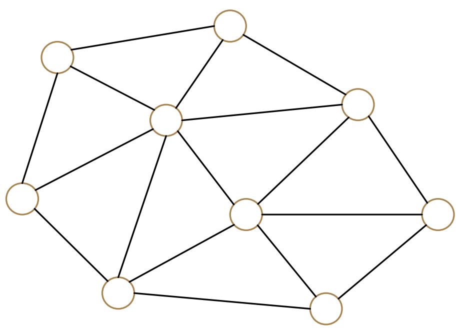

Figure 1.2: Mesh mode Topology.

SS

SS

In Mesh mode the concept BS refers the station which has a direct connection to the backhaul services outside the Mesh Network. All the others stations are termed SSs. Within Mesh Networks there are not Downlink or Uplink concepts.

Nevertheless a Mesh Network can perform similar as PMP, with the difference that not all the SSs must be directly connected with the BS. The resources are granted by the Mesh Bs. This option is termed Centralized Scheduling.

Concurrently there is another manner to schedule the transmissions, Distributed Scheduling. In this case all the stations even the Mesh BS must coordinate their transmissions with the others. And all the stations shall broadcast their schedules.

Both distributed or centralized scheduling algorithms have been considered in the standard for mesh mode operations. In general, in mesh mode all the nodes have to coordinate their transmissions in their two-hop neighbourhood and shall broadcast their schedules (available resources, requests and grants) to all their neighbours. In particular, nodes have to ensure that the resulting transmissions do not cause collisions with the data and control traffic scheduled by any other node in the two-hop neighbourhood.

1.3 Reference Model

The MAC layer in the IEEE Standard 802.16 is composed by three sublayers.

- Service-Specific Convergence Sublayer (CS): It provides any transformation or mapping of external network data.
- MAC Common Part Sublayer: This is the largest sublayer. It provides the core MAC functionality of system access, bandwidth allocation, connection establishment, and connection maintenance.
- Security Sublayer: It provides authentication, secure key exchange, and encryption.

It is shown in the following figure.

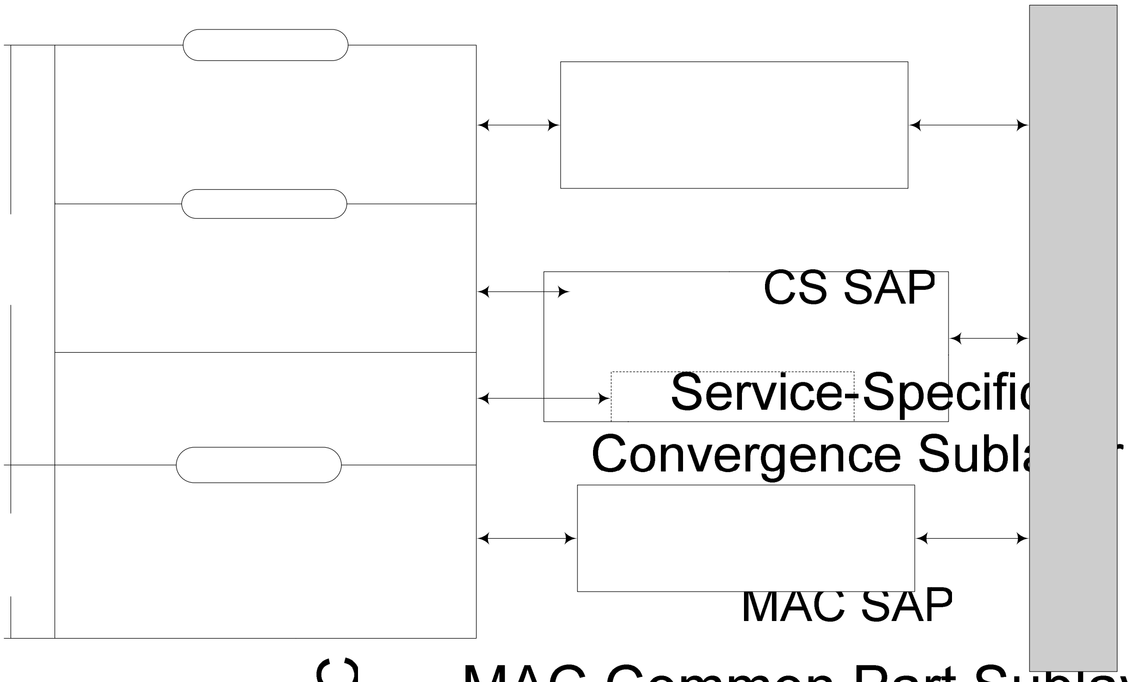

Figure 1.3: IEEE 802.16 Protocol layering

The first three sublayers constitute MAC layer and the other layer, PHY layer, shall be studied deeper.

1.3.1 MAC layer overview

As it is mentioned below, MAC layer embraces two main sublayers. Service-Specific Convergence Sublayer is used to map the transport-layer-specific traffic to a MAC that can efficiently transport any traffic type. The Common Part Sublayer is responsible for fragmentation and segmentation of MAC service data units (SDU) into MAC protocol data units (PDU), QoS control, and scheduling and retransmission of MAC PDUs. The bandwidth request and grant mechanism has been proposed to be scalable, efficient, and self-correcting. The 802.16 access system allows multiple connections per terminal, multiple QoS levels per terminal, and a large number of statistically multiplexed users. It provides a wide variety of request mechanisms.

1.3.2 PHY layer overview

The primary purpose of the PHY layer is to process correctly the raw bit information in order to minimize the errors at the receiver and maximize the throughput. For achieving the high performance levels required to support wireless broadband services, advanced modulation, equalization, multiplexing, diversity schemes and error control schemes are specified. The multiple versions of PHY layer are listed below [11]:

- WirelessMAN-SC: corresponds to the single-carrier version, designed to support LOS operation in the 10 to 66 GHz frequency range. The goal is to provide flexibility in LOS operation scenarios, in terms of planning, cost, services and capacity;
- WirelessMAN-SCa: this is the single-carrier solution for NLOS operation in frequencies below 11 GHz. The frame structure is designed to be robust against multipath fading. Furthermore, it supports Mobile receiver stations, channel estimation and equalization, space time coding, adaptive modulation, Automatic Repeat Request (ARQ), multiple error correcting coding schemes, Adaptive Antennas System (ASS), transmission diversity and power control.
- WirelessMAN-OFDM: designed to support NLOS operation in frequencies below 11 GHz, based on Orthogonal Frequency Division Multiplexing (OFDM), which consists of a multicarrier modulation scheme. This version extends the functionalities of version WirelessMAN-SCa, to support Mesh topology and subchannelization on the uplink, thus providing advanced resources for coverage optimization;
- WirelessMAN-OFDMA: this version supports NLOS operation in frequencies below 11 GHz, based on an Orthogonal Frequency Division Multiple Access (OFDMA), which consists of an extension of OFDM technique to allow multiple users access a shared channel. Number of carrier are scalable (some document; SOFDMA).It consists of many of WirelessMAN-SCa functionalities, including support to subchannelization on uplink and downlink;
- WirelessHUMAN: due to the support to functionalities for operation in license-exempt frequencies, this version is named “High-speed Unlicensed Metropolitan Area Network” (HUMAN). It can operate at frequencies between 5 and 6 GHz, which includes 10 and 20 MHz channels. However, the channelization scheme to be adopted in particular

deployment will depend on regulatory aspects. It is important noting that this version implements SCa, OFDM and OFDMA versions of PHY layer.

2. IEEE 802.16e TECHNICAL OVERVIEW and AMENDMENTS to IEEE 802.16-2004

2.1 Introduction

Although 802.16e is generally recognized as the mobile version of the standard, actually it serves the dual purpose of adding extensions for mobility and including new enhancements to the Orthogonal Frequency Division Multiplexing Access (OFDMA) physical layer. This new enhanced 802.16e physical layer is now being referred to as Scalable OFDMA (SOFDMA), a multi-carrier modulation technique that uses subchannelization to support scalable channel bandwidths from 1.25 MHz to 20 MHz. It includes a number of important features for fixed, nomadic, and mobile networks such as handover between WIMAX cells and roaming among WIMAX and other networks.

It is important indicating that this thesis is mainly focused in OFDMA PHY layer since it permits multiple accesses in the same band. Some aspects from Mobile WiMAX for Base Stations profiles are specified as optional in order to provide additional flexibility for deployment based on specific environments which may require different configurations that are either capacity-optimized or coverage-optimized.

High Data Rates: The inclusion of MIMO antenna techniques in addition with flexible sub-channelization schemes, Advanced Coding and Modulation enable the Mobile WiMAX technology to support High Data Rates in downlink and uplink.

Quality of Service (QoS): The fundamental premise of the IEEE 802.16 MAC layer is QoS (it is very important in 802.16-2004 Standard as well). It defines Service Flows that enable end-to-end IP based QoS. Additionally, sub-channelization and MAP-based signaling schemes provide a flexible mechanism for optimal scheduling of space, frequency and time resources over the air interface on a frame-by-frame basis.

Scalability: Since spectrum resources for wireless broadband worldwide are still quite disparate in its allocations, increasingly globalized economy, Mobile WiMAX technology therefore, is designed to be able to scale different channelizations from 1.25 to 20 MHz to consent with varied worldwide requirements as efforts proceed to achieve spectrum harmonization in the longer term. WirelessMAN-OFDMA PHY layer in the 802.16e Standard describes the OFDMA PHY. This mode is based on at least one of the FFT sizes 2048 (compatible to IEEE Std. 802.16-2004), 1024, 512 and 128 shall be supported. This shall facilitate support of the various channel bandwidths for example 1.25 MHz (128 size FFT), 5 MHz (512), 10 MHz (1024) and 20 MHz (2048).

The Mobile Station may implement a scanning and search mechanism to detect the DL signal when executing initial network entry and this could include dynamic detection of the FFT size and the channel bandwidth employed by the BS.

This also allows diverse economies to realize the multi-faceted benefits of the Mobile WiMAX technology for their specific geographic needs such as providing affordable internet access in rural settings versus enhancing the capacity of mobile broadband access in metro and suburban areas.

Security: The new features provided for Mobile WiMAX security aspects are best in class with EAP-based authentication, AES-CCM-based authenticated encryption, and CMAC and HMAC based control message protection schemes.

Mobility: Mobile WiMAX supports optimized handover schemes with latencies less than 50 milliseconds to ensure real-time applications such as VoIP perform without service degradation. Flexible key management schemes ensure that security is maintained during handover.

2.2 Physical Layer Description

Next paragraphs describe Physical Layer features. 802.16e Standard provides a further explanation of this layer, however for this thesis the description have been focused in main aspects.

2.2.1 OFDM Technique

Orthogonal Frequency Division Multiplexing (OFDM) is a crucial technique for supporting NLOS operation. It is used as well in WiFi technology due to the higher multipath robustness against path loss. OFDM is a multiplexing technique that subdivides the bandwidth into multiple frequencies sub-carriers:

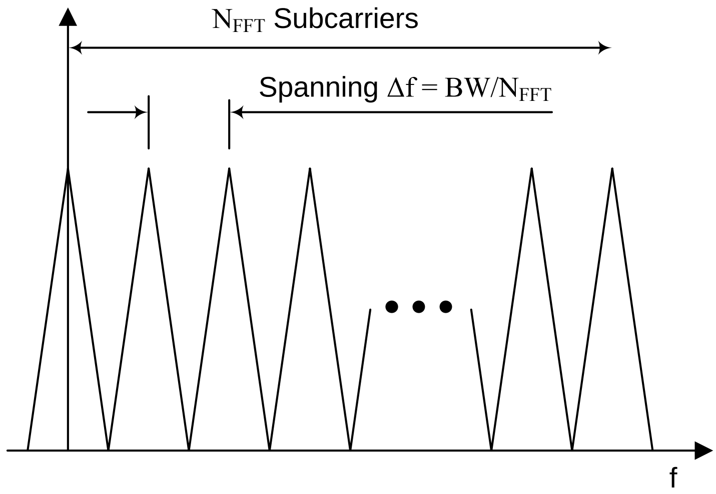

Figure 2.1: Orthogonal Sub-Carriers

In this case, a data stream transmitted at a rate of R bps is divided into several parallel sub-streams of reduced data rate, achieving a transmission rate of R/N bps, where N is the number of sub-carriers. By reducing data rate, symbol duration is increased. The increased symbol duration improves the robustness of OFDM to delay spread. Moreover, the introduction of Cyclic Prefix (CP) increases robustness against multipath fading and it can completely eliminate Inter-Symbol Interference (ISI). The CP is typically the last samples of data portion, of the useful symbol, appended to the beginning of the data payload as shown in next figure:

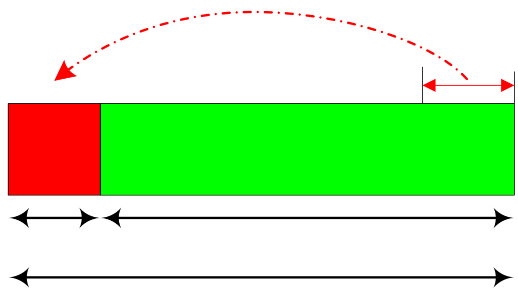

Figure 2.2: Symbol Structure with Cyclic Prefix (CP) insertion

2.2.2 OFDMA Symbol Structure and Sub-channelization

The OFDMA symbol structure consists of different types of sub-carriers as shown in Figure 2.3. The pilot sub-carrier does not carry data or signalling information, they are used for estimation and synchronization purposes (equalization, power control mechanism, etc). The DC sub-carriers allow the inclusion of guard band between groups of sub-carriers. This sub-carrier is defined in the Standard as “the sub-carrier whose frequency would be equal to the RF centre frequency of the station”. DC sub-carriers together with Guard sub-carriers (used for guard bands) are commonly denominated Null sub-carriers.

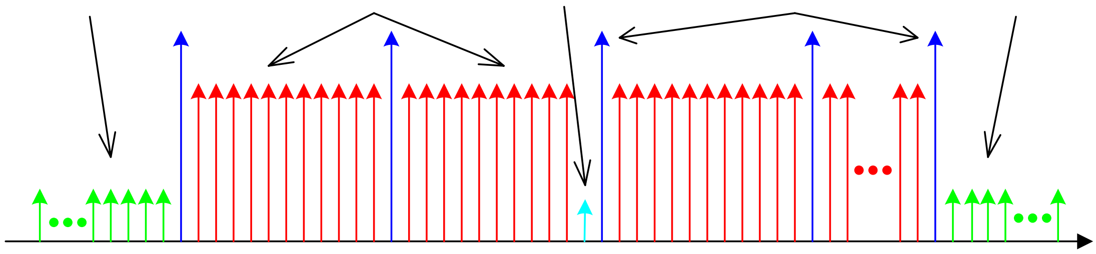

Figure 2.3: OFDMA Sub-Carrier Structure

Active sub-carriers (data and pilot) are group into subsets of sub-carriers called sub-channels. Sub-channelization in both DL and UL are supported by WiMAX OFDMA PHY. There are two types of grouping sub-carriers for sub-channelization: *diversity* and *contiguous.*

First one, ***diversity***, draws sub-carriers pseudo-randomly to form a sub-channel. Pseudo-random intercalation provides frequency diversity and inter-cell interference averaging. The Diversity permutation include DL FUSC (Fully Used Sub-Carrier), DL PUSC (Partially Used Sub-Carrier) and UL PUSC and additional optional permutations. This permutation technique will be further described below.

On the other hand, ***contiguous*** permutation draws contiguous sub-carriers to form a sub-channel. These permutations include DL AMC (Adaptive Modulation and Coding) and UL AMC, and have the same structure.

In general, diversity permutations perform well in mobile applications while contiguous permutations are well appropriated for fixed, portable or low mobility environments. For this reason, diversity permutations will be further explained for UL and DL.

In the case of **DownLink**, DL PUSC is mandatory and DL FUSC is an optional feature. Therefore DL PUSC sub-carrier group will be described. For this case, usable sub-carriers (pilot and data) are grouped in clusters. Each cluster contains 14 contiguous sub-carriers per symbol. Each cluster will be integrated by 12 data sub-carriers and 2 pilot sub-carriers with different distribution depending of the symbols number; even or odd as it is shown in next figure:

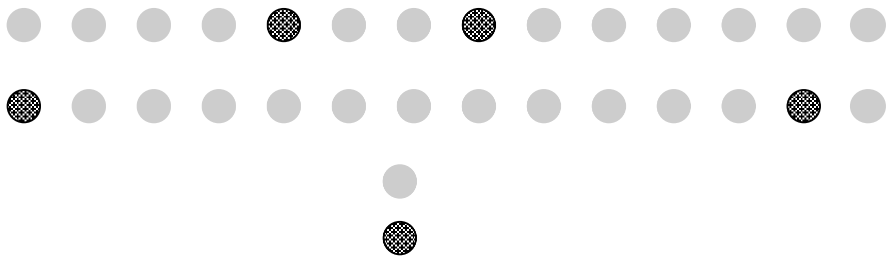

Figure 2.4: DL PUSC sub-channel

Only pilot positions in the cluster are shown, data sub-carriers in the cluster are distributed to multiple sub-channels. In the previous figure it can be noticed, as well, that a sub-channel contains 2 clusters and is formed up of 48 data sub-carriers and 8 pilot sub-carriers. It can be found out better with an example:

For 5 MHz Bandwidth channel there are 360 data sub-carriers and 60 pilot sub-carriers. Then, one cluster is formed by 12 data sub-carriers and 2 pilot sub-carriers, therefore there will be (360+60)/(12+2) = 30 clusters. Since each sub-channel is composed by 2 clusters, there will be 30/2 = 15 sub-channels in DL PUSC.

For **UpLink** the main group of sub-carriers change the name, in this case this group is called tile instead of cluster. This is defined for the UL PUSC where a sub-channel is constructed from six uplink tiles, each tile has four successive active sub-carriers and its format is as shown below:

Data

Pilot

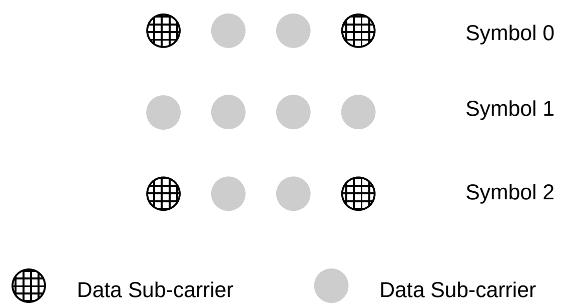

Figure 2.5: Tile Structure for UL PUSC

According to 802.16e Standard, a slot in the uplink is composed of three OFDMA symbols and one sub-channel, within each slot, there are 48 data sub-carriers and 24 fixed-location pilots. Hence, a sub-channel is formed by 24 usable sub-carriers. It can be realized better with an example:

In the case of 5 MHz Bandwidth, it can be found in 802.16e Standard that the number of all sub-carriers used in a symbol is 408 (409 minus DC sub-carrier). Then, because the number of sub-carriers for tile is 4, number of tiles is 408/4 = 102. At the same time, it is written that number of tiles for sub-channel is 6, therefore in a 5 MHz Bandwidth UL PUSC there are 102/6 = 17 sub-channels.

2.2.3 TDD Frame Structure

In spite of 802.16e Physical Layer supports TDD and Full and half-duplex FFD operations, TDD is defined for the initial mobile WiMAX profiles for its added efficiency in support of asymmetric traffic and channel reciprocity for easy support of advanced antenna systems, although TDD does require global synchronization..

When implementing a TDD system, the frame is built from BS and SS transmissions. Next figure illustrates the OFDM frame structure for a Time Division Duplex (TDD) implementation. Each frame is divided into DL and UL sub-frames separated by Transmit/Receive and Receive/Transmit Transition Gaps (TTG and RTG, respectively) to prevent DL and UL transmission collisions.

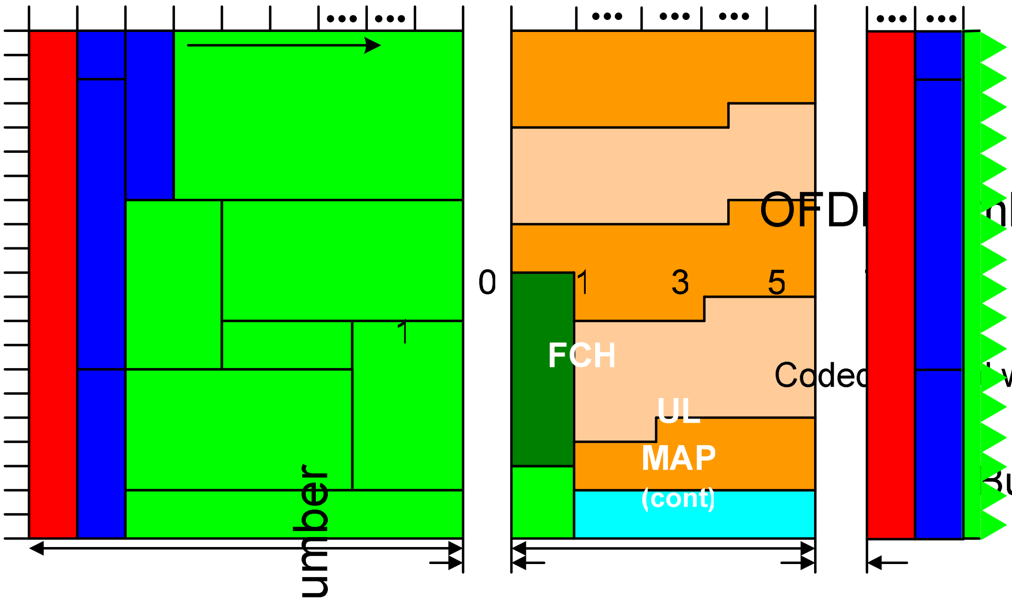

Figure 2.6: WiMAX OFDMA Frame Structure [19]

Each frame in the transmission starts with a preamble (incorporated in the Downlink subframe) followed by a DL transmission period and UL transmission period. Besides preamble, other control information is inserted in the frame structure. In the Downlink subframe DL-MAP and UL-MAP are used to provide sub-channel allocation and other control information for the DL and UL sub-frames respectively. At the same time in this subframe FCH is added to provide frame configuration information. On the other side, UL subframe incorporates Ranging and optional CQICH and ACK-CH.

2.2.4 Advanced PHY layer features

Within Mobile WiMAX QPSK, 16-QAM and 64-QAM are mandatory in the DL. In the UL 64-QAM is optional. It also supports Convolutional Code (CC) and Convolutional Turbo Code (CTC) with variable code rate. These are the mandatory modulation features; however Block Turbo Code and Low Density Parity Check Code (LDPC) are optional. This set of different modulation techniques is commonly denominated Adaptive Modulation and Coding (AMC) and it provides a fine resolution of data rates depending of the Mobile Station.

A new feature of Mobile WiMAX is the Channel Quality Information (CQI) Channel (CGICH) which is used to provide channel-state information from the

Mobile Terminal to the Base Station scheduler. This information shall include: Physical CINR, effective CINR, MIMO mode selection and frequency selective sub-channel selection. With this information Base Station scheduler shall determine the appropriate data rate for each burst allocation. This feature is also mentioned with 802.16-2004 Standard but it completely introduced in Mobile WiMAX.

As in the case of CQICH, Hybrid Auto Repeat Request (HARQ) is briefly described in 802.16-2004 Standard as an optional feature. HARQ is made capable using N channel "Stop and Wait" protocol which provides fast response to packet errors and improves coverage. A dedicated ACK channel is provided in the uplink for HARQ ACK/NACK signalling which allows fully asynchronous operation. The asynchronous operations are more flexible to the scheduler at the cost of additional overhead for each retransmission allocation.

The combination of HARQ, CQICH and AMC increase coverage and capacity for WiMAX in mobile applications. They provide a robust link adaptation in mobile environments at vehicular speeds up to 120 km/h.

2.3 MAC Layer Description

Since the beginning 802.16 Standard has been developed for the delivery of broadband services including voice, data and video. It can support bursting data simultaneously with streaming video and latency-sensitive voice traffic over the same channel. Since the resource allocation information is carried in the Map messages within the beginning of each frame, explained in 3.2.3, the MAC scheduler can effectively change the resource allocation on any frame. It can vary the resource to one terminal from a single time slot to the complete frame; this is basic to adapt the bursting nature of the traffic.

Quality of Service (QoS) Support and Mobility Management are the most important features for this thesis (they will be further explained) however other features can not be despised. Mobile WiMAX adds a MAC scheduling service which is designed to efficiently deliver broadband data services such us voice, data and video overtime varying broadband wireless channel. This service has the following properties: Fast Data Scheduler, Scheduling for DL and UL, Dynamic Resource Allocation, QoS Oriented and Frequency Selective Scheduling.

On the other hand, as it is mentioned in the Introduction of this point (IEEE 802.16e Technical Overview and Amendments to IEEE 802.16-2004), Mobile WiMAX supports best in class security features by adopting the best technologies available today. Mobile WiMAX can support device/user authentication, flexible key management protocol, strong traffic encryption, control and management plane message protection and security protocol optimization for fast handovers.

2.3.1 Quality of Service (QoS) Support

In the Mobile WiMAX MAC Layer, QoS is provided via service flows. This service is a unidirectional flow of packets which are provided with a particular set of QoS parameters. The Base Station and the Subscriber Station establish a unidirectional logical link between the peer MACs called connection. After connection establishment, the QoS parameters, depending of the application, define the transmission ordering and scheduling on the air interface. Therefore QoS (connection-oriented) can provide exact control over the air interface. This service flow is supported for both directions, DL and UL. The management of service flow parameters is realized by exchange of MAC messages.

Table 2.1 Mobile WiMAX Applications and Quality of Service [19]

QoS Category	Applications	QoS Specifications
UGS Unsolicited Grant Service	VoIP	Maximum Sustained Rate Maximum Latency Tolerance Jitter Tolerance
rtPS Real-time Polling Service	Streaming Audio or Video	Minimum Reserved Rate Maximum Sustained Rate Maximum Latency Tolerance Traffic Priority
ErtPS Extender Real-Time Polling Service	Voice with activity Detection (VoIP)	Minimum Reserved Rate Maximum Sustained Rate Maximum Latency Tolerance Jitter Tolerance Traffic Priority
nrtPS Non-Real-Time Polling Service	File Transfer Protocol (FTP)	Minimum Reserved Rate Maximum Sustained Rate Traffic Priority
BE Best-Effort Service	Data transfer, Web browsing, etc	Maximum Sustained Rate Traffic Priority

Mobile WiMAX supports a wide range of data services and applications with diverse QoS requirements. These different applications are summarized in the table shown above.

2.3.2 Mobility Management

The IEEE 802.16e Standard defines a framework for supporting mobility management. Battery life and handoff are two critical issues for mobile applications.

Power Management

In order to support battery-operated portable devices, mobile WiMAX has power-saving features that permit portable Subscriber Stations to operate for longer periods of time without having to recharge. Power saving is achieved by turning off parts of the Mobile Station in a controlled manner when it is not actively transmitting or receiving data. Mobile WiMAX defines signaling methods that allow the Mobile Station to retreat into two different modes: sleep mode or idle mode when inactive.

Sleep mode is a state in which the MS effectively turns itself off and becomes unavailable for predetermined periods, to DL or UL traffic. The periods of absence are negotiated with the serving Base Station. Sleep mode is intended to minimize

Mobile Station power usage and therefore air interface resources. To facilitate handoff while sleep mode, the MS is allowed to scan other Base Stations to collect information related with handoff.

Idle mode permits even greater power savings. Idle mode allows the MS to completely turn off and to become periodically available for DL broadcast traffic messaging without registration at a specific Base Station as the MS cross an air link environment populated by many Base Stations. Idle Mode profits the Mobile Station by eliminating the requirement for handoff and other normal operations and benefits the network and Base Station by removing air interface and network handoff traffic from mainly inactive Mobile Stations while still providing a simple and opportune method (Paging) for alerting the Mobile Station about pending DL traffic.

Handoff

The IEEE 802.16e Standard defines signaling mechanisms for tracking Subscriber Stations as they move from the coverage range of one base station to another when active mode or as they move from one paging group to another when idle mode. The Standard supports seamless handoff to permit the MS to switch from one BS to another at vehicular speeds without interrupting the connection.

Three handoff methods are supported in IEEE 802.16e Standard; one is mandatory and other two are optional. The mandatory handoff method is called the hard handoff (HHO) and is the only type required to be implemented by mobile WiMAX certified products initially. HHO implies an abrupt exchange of connection from one BS to another. The handoff decisions are made by the BS, MS, or another entity, based on measurement results reported by the Mobile Station. The Mobile device periodically does scan of frequency and measures the signal quality of neighbouring Base Stations. During these intervals of time, the Mobile device is also allowed to optionally execute initial ranging and to associate with one or more neighbouring Base Stations. Once a handover decision is made, the MS begins synchronization with the DL transmission of the objective BS, performs ranging if it has not been realized while scanning, and then terminates the connection with the previous BS. Any undelivered MAC PDUs at the BS are retained until the timer finish.

The two optional handoff methods supported by Mobile WiMAX are Fast Base Station Switching (FBSS) and Macro Diversity Handover (MDHO). In both methods, the MS maintains a valid connection at the same time with more than one BS. In the FBSS case, the MS maintains a list of the Base Stations included, this list is called the Active Set. The MS constantly monitors the Active Set, performs ranging, and maintains a valid connection ID with each of them. However the MS only communicates with the Anchor BS, from the Active Set, for uplink and downlink messages including management and traffic connections. When a change of anchor BS is required, the connection is switched from one base station to another without invocation of explicitly handoff signaling messages. The MS simply reports the selected anchor BS on the CQICH. An important requirement of FBSS is that data is simultaneously transmitted to all members of an Active Set of Base Stations that are able to serve the MS.

Macro diversity handover is similar to FBSS about Active Set and Anchor BS, except that the MS communicates with all the Base Stations in the Active Set simultaneously of downlink and the uplink unicast messages and traffic. A MDHO commences when a MS decides to transmit or receive unicast messages and traffic from various Base Stations in the same time interval. In the downlink, multiple copies received at the MS are combined using diversity combining techniques. In the uplink, the MS sends data to multiple Base Stations, where selection diversity of the information received is performed to pick the best uplink.

Both FBSS and MDHO offer better performance to HHO, but they require that Base Stations are synchronized, use the same carrier frequency and share network entry information. Support for FBHH and MDHO in Mobile WiMAX networks is not fully developed yet and is not part of WiMAX Forum Release 1 network specifications.

2.4 Comparison between 802.16-2004 and 802.16e profiles

The amendments introduced in 802.16-2004, by incorporating features of previous versions, were focused on fixed and nomadic applications in the 2-11 GHz. Two multi carrier modulation techniques are supported in 802.16-2004: OFDM and OFDMA with 256 and 2048 sub-carriers respectively. Although the Standard supports both modulation techniques, first WiMAX Forum certification profiles are based on OFDM.

At the same time, as 802.16-2004, 802.16e-2005 incorporates features of previous versions and adds support for mobile access. This mobility support is based on Scalable OFDMA. This aspect will be studied since different modulation techniques mean different performances. Since they are not the same modulation technique, OFDM and OFDMA are not compatible.

There are several optional features that are supported in 802.16-2004 profile and they are implemented in 802.16e in order to obtain a better performance for mobile services. Among these functionalities, improved support for MIMO and AAS will contribute for a considerable increase in throughput and NLOS capabilities. In the same set of functionalities, HARQ and CQICH are mentioned in 802.16-2004 as optional features, further explained in paragraph 3.2.4.

2.4.1 OFDM and OFDMA

A key difference between Fixed and Mobile WiMAX is the multiplexing technique: they use OFDM and OFDMA respectively. OFDM multiplexing technique is less complex than Scalable OFDMA, thus 802.16-2004 WiMAX Forum Certified products are supposed to be lower cost than future Mobile WiMAX products. Therefore Fixed WiMAX network may be deployed faster by using directional antennas.

On the other hand, OFDMA gives 802.16e profiles more flexibility for managing different devices with variety of antenna types and form factors. This means a reduction in interference with omnidirectional antennas and improved NLOS capabilities. Within this multiplexing technique, subchannelization is defined as a group of different sub-channels which can be allocated to different subscribers depending of the channel condition and their data requirements. These features introduce wide flexibility in managing the bandwidth and transmit power.

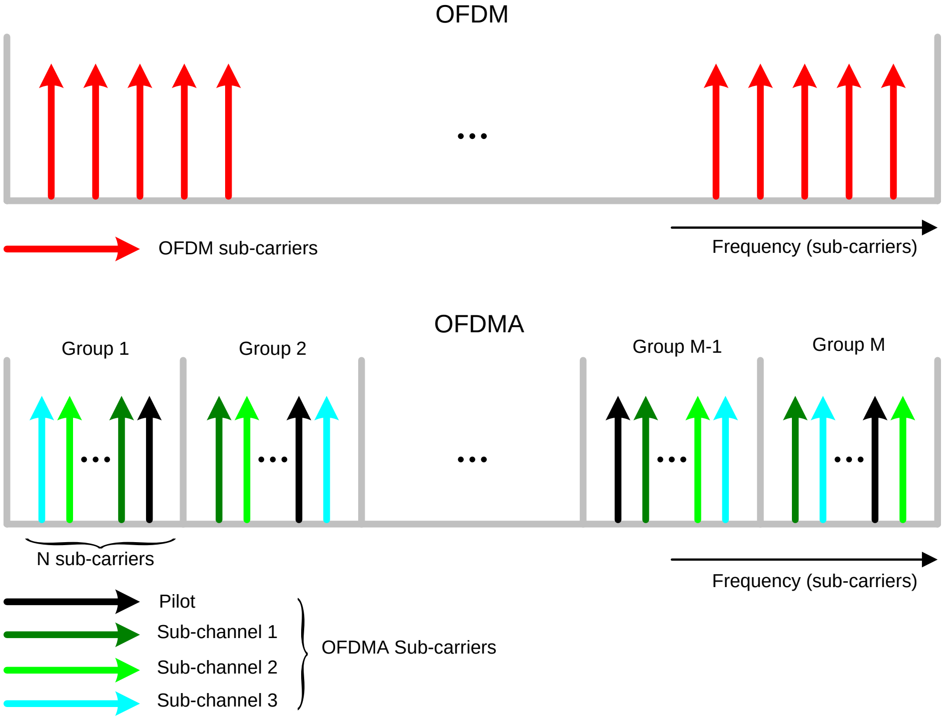

Figure 2.7: OFDM and OFDMA [20]

In the figure above it can be noticed that in OFDM all sub-carriers are transmitted in parallel with the same amplitude. Contrary, OFDMA divides the sub-carriers space into M sub-channels with N sub-carriers each sub-channel. For instance, OFDMA of 1024 sub-carriers is divided in 30 sub-channels of 28 sub-carriers in the Downlink and 35 sub-channels of 24 sub-carriers in the Uplink, including in these groups Data and Pilot sub-carriers. Coding, modulation and amplitude are set separately for each sub-channel based on channel conditions to optimize the use of network resources.

In OFDM subscriber devices are assigned time for Uplink transmissions. The slot can be only used by one user device, it can be observed in the next figure where the first user will use every 256 sub-carriers for the transmission. Contrary, in OFDMA, subchannelization in the Uplink enables various Subscriber Stations to transmit at the same time over the sub-channel(s) allocated to them.

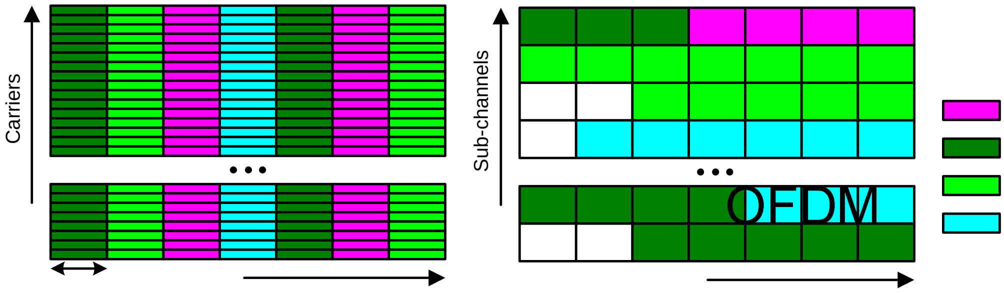

Figure 2.8: Uplink in OFDM and OFDMA [20]x

OFDMA within 802.16e Standard has additional advantage since it can scale the number of FFT according to the channel Bandwidth (128, 512, 1024 or 2048). It changes the number of FFT in order to keep the sub-carrier spacing constant across different channel Bandwidths. By keeping this value the bandwidth is better utilized.

2.4.2 Handoffs

Support for handoffs is another key addition in the 802.16e amendment for mobile access. The capacity of maintaining a connection, while moving across coverage borders of Base Stations, is a prerequisite for mobility and it is included as a requirement in the 802.16e Standard. While the 802.16-2004 Standard offers optional handoff capabilities, support for handoffs is not required by the Fixed WiMAX profiles.

Mobile WiMAX will support different types of handoff, from hard to soft and it will be up to the operator to choose among them, although only Hard Handoff (HHO) will be mandatory. Hard handoffs use a period of time before make the approach, the user device is connected to only one Base Station at any given time, which is less complex than soft handoffs but has a higher latency. Soft handoffs are comparable to those used in some cellular networks and allow the user device to retain the connection to a Base Station until it is associated with a new one, thus reducing latency. While applications like mobile Voice over Internet Protocol (VoIP) or gaming greatly benefit from low-latency soft handoffs, hard handoffs typically suffice for data services.

3. ADDITIONAL INFORMATION

As it is mentioned before in the Introduction, the investigation of coverage and theoretical maximum throughput in the new 802.16e Standard, Mobile WiMAX is the aim of the Thesis. For this target, it is essential explaining the process from the beginning.

Performance analysis requesting information can be almost completely obtained from 802.16-2004 and 802.16e-2005 Standards, with the complement of WiMAX Forum certified profiles. Here it can be found out the necessary information for the calculations of theoretical maximum throughput. This value will be decreased mainly because three factors: PDU header, guard time and pilot sub-carriers. This information is not only related with the Physical Layer, also MAC Layer influences in the maximum throughput.

For the case of **coverage prediction**, principally, it must be shown the basic formula of a link budget:

$$P_r = P_t + G_t - PL + G_r \tag{3.1}$$

where P_r is the minimum received power in the receiver, is usually related with the Sensitivity, P_t is the transmitted power, G_t is the gain of the transmitter, PL is the Path Loss, it depends of the environment and G_r is the gain of the receiver.

Therefore, all of these parameters must be explicated before being used. Thus, in the next point, all the parameters are further explained. First of all, it must be shown the specifications of 802.162 Standard, although this information will not be used for the receiver sensitivity since the thesis will be more focused in the actual certificated products. For this reason some of the certificated products will be studied. At the same time, different Propagation Model will be examined in order to get correct information for each environment.

This link budget would not have purport without information about the work frequency, since it is known for all that Frequency conditions completely the calculations. In this point, at the same time, number of sub-carriers is further described depending of the frequency band and direction; downlink or uplink.

3.1 Standard Mobile WiMAX parameters

First of all, Standard Mobile WiMAX parameters must be described. All of this information can be found in 802.16-2004 and 802.16e-2005 Standards. These data are divided into two groups according to the target of investigation. The first point is related with the maximum radius coverage and the following one is relevant with maximum throughput.

3.1.1 Receiver sensitivity in Mobile WiMAX technology

Although the minimum sensitivity for the receiver is not going to be used according to the Standard, this value has extremely importance since is the principle for certificated products. The receiver minimum sensitivity level, RSS, is derived according to next Equation [1]:

$$P_{r,\min} = -114 + SNR_{Rx} - 10\log R + 10\log\left(\frac{F_S N_{used}}{N_{FFT}}\right) + \mathrm{Im}\,pLoss + NF \qquad \textbf{(3.2)}$$

where,

SNR_{Rx} is the receiver SNR as in the Table 3.1.

R is the repetition factor. It can take the next values: 2, 4 or 6. The difference between the best case (R = 6) and the worst case (R = 2) is 4.77dB.

F_S is the sampling frequency in MHz (4.1.2.1).

ImpLoss is the implementation loss, which includes non-ideal receiver effects such as channel estimation errors, tracking errors, quantization errors, and phase noise. The assumed value is 5 dB.

NF is the receiver noise figure, referenced to the antenna port. The assumed value is 8 dB.

Table 3.1 Receiver SNR assumptions [1]

Modulation	Coding Rate	Receiver SNR (dB)
QPSK	1/2	5
	3/4	8
16-QAM	1/2	10.5
	3/4	14
64-QAM	1/2	16
	2/3	18
	3/4	20

This table has been modified in 802.16e-2005 Amendment, their values have been changed. And they can be modified further, depending of the new WiMAX profiles. It is important to notice that N_{used} in this case is the set of pilot and data sub-carriers because it is related with the required power for those usable sub-carriers. Remind that pilot sub-carriers are used for management information.

According to this formula, some values have been calculated for QPSK, 16-QAM and 64-QAM Modulation and 5 MHz and 10 MHz Channel Bandwidth. These parameters have been utilized since they are the most interesting for this thesis. It will notice below, in others paragraphs, that there already are these two channels certified by WiMAX Forum.

These calculated values will be compared with the values provided by the device producers in order to find out the differences and similitudes.

Table 3.2 Receiver Sensitivity (dB) according 802.16e Standard

			5 MHz	10 MHz
	Nfft		512	1024
	Nused		420	840
QPSK	1/2	5	-92,30	-89,29
	3/4	8	-89,30	-86,29
16-QAM	1/2	10,5	-86,80	-83,79
	3/4	14	-83,30	-80,29
64-QAM	1/2	16	-81,30	-78,29
	2/3	18	-79,30	-76,29
	3/4	20	-77,30	-74,29

Above minimum required receiver sensitivity according to 802.16e-2005 Standard is shown. This is the minimum value required by the Standard however companies may make even better products with a lower Noise Figure which is the main point of improvement.

3.1.2 Performance Analysis

Different literatures use various different statics in measuring the performance of wireless network. Throughput is defined as the amount of data (bits) transferred successfully from one node to another in a specified amount of time. This definition is the same in Mobile WiMAX where it can be found the formula to calculate it in the Standard. At the same time, it can be forgot that many aspects in the MAC layer decrease the total throughput such as: header, subheader, CRC, preamble, etc. Therefore, it is also important to explain all of these overloads.

Physical layer throughput

As it is mentioned before the physical layer throughput is defined in the Standard although it only defines it as all people know; amount of data (bits) transferred successfully from one node to another in a specified amount of time. Thus, in 802.16-2004 Standard [4]rata bit rate is defined for OFDM physical layer as:

$$R = \frac{N_{used}\, b_m\, c_r}{T_S} \quad \textbf{(3.3)}$$

where b_m is the number of bits per modulation symbol and c_r is the coding rate. The symbol duration T_S, according to Figure 2.2, is given by

$$\begin{aligned} T_S &= T_g + T_b \\ &= [G+1]T_b \end{aligned} \quad \textbf{(3.4)}$$

where G is the ratio T_g/T_b, this value can be: 1/4, 1/8, 1/16 or 1/32. And $T_b = 1/\Delta f$, with the sub-carrier spacing Δf is given as

$$\Delta f = \frac{F_S}{N_{FFT}} \quad \textbf{(3.5)}$$

and,

$$F_S = floor\left({}^{nBW}\!\big/_{8000} \right) 8000 \quad \textbf{(3.6)}$$

where F_S is the sampling frequency, n is the sampling factor, BW is the nominal channel bandwidth and N_{FFT} is the number of points for FFT.

The Sampling factor in conjunction with BW and N_{used} determines the sub-carrier spacing, and the useful symbol time. This value has changed from OFDMA 802.16-2004 Standard is set to 8/7 as follows: for channel bandwidths that are a multiple of 1.75 MHz then n = 8/7 else for channel bandwidths that are a multiple of any of 1.25, 1.5, 2 or 2.75 MHz then n = 28/25 else for channel bandwidths not otherwise specified then n = 8/7.

This is the theoretical and direct calculation however it should take into account that for example that T_S period corresponds to Figure 2.2, therefore R must be reduced in a factor of 4/5, 8/9, 16/17 or 32/33 according to the configuration. Only those rates of T_S period are used for data payload.

At the same time, it can be noticed in Figure 2.3 that not every OFDMA symbol is used for data. According to [5] Mobile WiMAX uses only 44 data OFDMA symbol from a total of 48. This reduction of performance will take into account in the calculations.

Next figure shows information about two different possible bandwidths 5MHz and 10MHz which will be used for the research. Number of sub-channels are calculated according to paragraph 2.2.2 depending if it is downlink or uplink.

Table 3.3 OFDMA scalability parameters

Parameter	Downlink	Uplink	Downlink	Uplink
System Bandwidth	5 MHz		10 MHz	
FFT size	512		1024	
Null sub-carriers	92	104	184	184
Pilot sub-carriers	60	136	120	280
Data sub-carriers	360	272	720	560
Sub-channels	15	17	30	35
Frame duration	5 milliseconds			
OFDMA symbol/frame	48			
Data OFDMA symbols	44			

Within the table it can be observed that number of Data OFDMA symbols is only 44 from 48. This is because 1.6 symbols are used for TTG and RTG gaps and the rest from 4 OFDMA symbols are used for locating other useful information such as UL-MAP, DL-MAP or FCH.

MAC layer overload

Connections are also affected but the MAC Layer. All MAC PDUs are required to load some overload for different purposes. Minimum overload would be 10 bytes (6 bytes of header and 4 bytes of CRC) of a total amount of 2047 bytes. This load is not considerable by if MAC PDUs must to be overload with different subheaders such us Mesh, Fragmentation or Packing subheaders, this will influence in the efficiency of the connections by decreasing the maximum throughput.

Below some different MAC PDU formats are shown:

Generic MAC header (6bytes)	Mesh Subheader (2bytes)	Payload (optional)	CRC (4bytes)

Generic MAC Header	Other subheaders	Fragmentation subheader	Payload (One SDU or fragment of an SDU)	CRC-32

Generic MAC header	Grant Manage-ment subheader (UL only)	Packing subheader	Payload (One SDU or SDU fragment or a set of ARQ Feedback IEs)	...	Packing subheader	Payload (One SDU or SDU fragment)	CRC-32

Figure 3.1: Different MAC PDU formats

Although it is clear that these different configurations would have different performances, this influence is not going to be studied since the complexity of developing a formula for knowing how many PDU would be fragmented or packed for instance.

3.2 Current equipment parameters

There are various devices which can perform Mobile WiMAX. There exist many different certified products from few companies since, although most of wireless companies are interested on developing WiMAX devices, they did not get yet a certified product. In the next paragraphs some of these certified products will be presented, focusing in the most important features for the research, such as: Frequency Band, Channel Size (FFT), Minimum sensitivity, transmitter and receiver gain and transmitted power.

There are two important aspects for noticing. First one, although devices are able to transmit a high power, this transmitted power is limited by CPE (Costumer Promise Equipment); therefore for calculations these supervised values will be used. The second important aspect is that, since Mobile WiMAX supports VoIP (Voice over IP), connection between Base Station and Mobile Station can be limited by uplink given that the transmitted power of the Mobile Station is lower than Bases Station's. This is because Mobile Station will be usually closer to people that Base Stations. Anyway coverage prediction will use Base Station as transmitter and Mobile Station as receiver in order to ease calculations.

3.2.1 Available Products

Since Mobile WiMAX profiles have not been developed yet, it is especially difficult to describe the properties of the future devices. In the cases there are not data sheets of Base and Subscriber Station, the aim of the thesis will be finding the new Sensitivity from Fixed WiMAX devices.

Airspan has already developed future device for Mobile WiMAX therefore, the values of gain, transmitted power and Sensitivity will be directly accepted. In other cases calculations will have to be realized. This causes that table made below with all companies contains information contributed by the company's website (Airspan) and calculated information from company's website. Then, table will be made just to provide an idea of different devices, but it will not be very useful for a acceptable comparison.

In order to determine new sensitivity value for Mobile WiMAX next formulas will be used. Thus, Noise is defined as:

$$N = -174 + 10\log BW + NF \qquad \textbf{(3.7)}$$

and sensitivity:

$$S_{\min} = N + SNR \qquad \textbf{(3.8)}$$

then,

$$S_{\min} = -174 + 10\log BW + NF + SNR \qquad \textbf{(3.9)}$$

Within these formulas, in those cases where Companies have not already developed equipments for Mobile WiMAX, the values of Bandwidth, Noise Figure and SNR will changed in accordance with 802.16-2004 and 802.16e-2005 Standards.

Most of equipment manufacturer define the sensitivity at the lowest bandwidth and modulation, usually 3.5 MHz at BPSK 1/2. Moreover, since their products are designed for Fixed WiMAX they are developed for OFDM PHY layer. Then, they use SNR requirements from point 8.3.11.1 in [5] and for this thesis the values must be in accordance with SNR requirements from point 8.4.13.1.1 in [1].

At the same time Bandwidth (in this thesis 5 and 10 MHz) and Noise Figure must be in accordance with the new requirements from 802.16e-2005 Standard. Therefore Noise Figure will have a value of 8 dB instead of the 7 dB used in 802.16-2004 Standard. And the sensitivity will be modified in accordance with the new Bandwidth.

Thus, for instance, when a Subscriber Station designed for Fixed WiMAX (developed for OFDM PHY) had a sensitivity of -98 dBm at BPSK 1/2 (SNR = 6.4 dB) and bandwidth of 3.5 MHz, new sensitivity for QPSK 1/2 (SNR = 5 dB) and 5 MHz bandwidth would be:

$$S_{NEW} = -98 + (-6.4 + 5)_{SNR} + 10\log\left({5\,MHz}\big/{3.5\,MHz} \right) + (-7 + 8)_{NF} \approx -97dBm \quad \textbf{(3.10)}$$

In accordance with this calculation, sensitivity for every Fixed WiMAX device will be calculated. Thus, comparison with Table 3.2 can be realized in order to find a value for sensitivity which represents the logic average of all of those values.

Some WiMAX companies are described below. Only main companies have been selected from WiMAX Forum Certified products. All of these products are already certified for Fixed WiMAX, but few presented devices for Mobile WiMAX did not get the certification yet.

Airspan

The first product of Airspan was based on CDMA radio technology. It was adapted for fixed wireless access and was a market success. The company currently provides a wide range of WiMAX Base Stations and customer premise devices. The company currently has over 100 engineers developing Mobile WiMAX solutions.

This company has already made an effort to develop new and old device for the new standard IEEE 802.16e. Some of the devices will be able to work with Mobile WiMAX in the future however they are not capable to operate in 2.3 GHz frequency band, therefore these devices will not be interesting for this thesis. They are EasyST-

2 and ProST-2. On the other hand in Airspan's catalogue it can be found two possible Base Stations and one Mobile Station:

- **Base Station**: MicroMAXe and MacroMAXe. Both initially support 5MHz and 10MHz channel sizes. However, the product is capable of supporting 20MHz channels (Mobile WiMAX profile Rel. 1.5) as well. Both have been designed to support either 2x10MHz and 2x5MHz (using dual PHY/MAC) or 1x20MHz channel. They support 512, 1024 and 2048 FFT Scalable OFDMA. MacroMAXe is optimized for 2.3 GHz and 2.5 GHz frequency bands whereas MicroMAXe comprises wider range of frequency bands.
- **Mobile Station**: It consists in a WiMAX USB and it supports Mobile WiMAX. The WiMAX USB packs a big RF performance despite it is diminutive size delivering up to +22dBm into the antenna. The product is capable of supporting 10MHz, 8.75MHz, 7MHz and 5MHz (1024 and 512 FFT Scalable OFDMA). It can operate in wide range of frequency bands as MicroMAXe.

Alvarion

Alvarion was one of the first companies to produce 802.11 WLAN equipments. Within WiMAX system, currently, BreezeMAX is the most important product for Alvarion. It keeps the companies into the selected company's BWA industry leadership. At the same time Alvarion will be one of the first companies offering mobile WiMAX although only new family's member BreezeMAX 2300/2500/3500 were ready when this thesis was written.

Then, BreezeMAX is the family of WiMAX products for Alvarion. It comprises Base Station as well as Subscriber Station (indoor and outdoor). Within this family BreezeMAX 2300/2500/3500 Subscriber Stations will be used for getting required information and , on the other hand, general features for Base Stations will be obtained from [16] (alv_BreezeMAX_pbp.pdf).

- **Base Station**: BreezeMAX Base Station solution features advanced OFDM technology to support NLOS operation, adaptive modulation up to QAM64, and the highest spectral efficiency available. Operating in the

3.3, 3.5 and 3.6 GHz licensed frequency bands. Different bandwidth can be software selected (3.5 and 1.75MHz).

- **Mobile Station**: This Mobile Station is operating in 2.3, 2.5, and 3.5 GHz and related licensed frequency bands. The product is capable of supporting 10MHz, 7MHz, 5MHz and 3.5MHz (software selectable). Although it is designed for 802.16e-2005 Standard, it does not support yet Scalable OFDMA. The sensitivity is also described for OFDM FFT 256, therefore it must be also extrapolated. Antenna has different gains depending on the frequency band. It is TDD-based platform.

Axxcelera

Axxcelera Broadband Wireless is a data networking solutions company, developing technology to deploy networks for broadband wireless communications over Internet. ExcelMAX and AB-MAX fixed wireless broadband platforms are used to bridge the last mile of broadband wireless communications, with a point-to-multipoint solution. Axxcelera has put together their ExcelMAX and Excel Air products for Licensed WiMAX, and their AB MAX and AB Access for Unlicensed WiMAX applications.

- **Base Station**: Axxcelera's ExcelMAX Base Station is a Point to Multipoint (PMP) BS product designed to operate in the 3.3-3.8 GHz spectrum and supports Full FDD (Frequency Division Duplex) architecture. The 802.16-2004 Standard compliant NLOS platform supports a strong suite of Quality of Service (QoS) features and multiple services. The product is capable of supporting 14 MHz (optional), 7 MHz, 3.5 MHz and 1.75 MHz bandwidths. Antenna has different gains depending on the degrees; 60 or 90.

- **Subscriber Station**: Axxcelera's ExcelMAX Indoor CPE is a self-installable Point to Multipoint (PMP) CPE designed to operate in the 3.3-3.8 GHz spectrum and supports a Half Duplex FDD (Frequency Division Duplex) or TDD (Time Division Duplex) architecture. NLOS operations are supported. It works only in 7 and 3.5MHz channel size. And the antenna has a gain of 10dBi with 90 degrees. The ExcelMAX CPE 3400 supports also a strong suite of Quality of Service (QoS) features, including Committed Information Rate (CIR), Peak Information Rate (PIR), BE, nrtPS, rtPS, and UGS.

Redline

Redline Communications is a technology company specialized in the design and manufacture of standards based on broadband and wireless access solutions. Redline launched its family of WiMAX products called RedMAX. The RedMAX family includes products for each of the 802.16 variants (a, 2004) and to guarantee also that future of the next amendment of IEEE 802.16 Standard (802.16e) to support mobility, although they were available when this thesis was written.

- **Base Station**: RedMAX AN-100U is a High performance PMP Base Station platform. It operates in the 3.3 to 3.5; 3.4 to 3.6; and 3.6 to 3.8 GHz RF bands. It supports 2nd generation 802.16 MAC layer and 3rd generation OFDM PHY layer, 7 and 3.5 MHz bandwidth are supported. Maximum transmitted Power is 23 dBm across all modulation/coding levels. It has a extremely low latency and superior reliability. Dynamic QoS.
- **Subscriber Station**: RedMAX Subscriber Unit is 802.16-2004 Standard compliant. It operated in the 3.3 to 3.5; 3.4 to 3.6; and3.6 to 3.8 GHz RF bands. This Subscriber Station has self-installation. 7 and 3.5 MHz bandwidth are supported as well as extremely low latency. 24 dBm is the maximum transmitted Power. Dynamic Quality of Service (QoS) settings are also supported.

Telsima

Telsima Corporation is a leading developer and provider of WiMAX based Broadband Wireless Access and mobility solutions for media rich applications. The Company develops and markets Base Station and Subscriber Station systems and network management software for the WiMAX telecommunications market.

They have developed already two Subscriber Stations for 802.16e Standard (StarMAX 3100 and 3200), however, in the website too few information is provided about these future products. Therefore, in the same line than previous companies, old devices will be used in order to provide guiding information.

This family is called StarMAX and it contains Base Station (6400) and Subscriber Station (2100). Actually, they are both Fixed WiMAX-designed, however, they can be configured to support of IEEE 802.16e-2005 Mobile WiMAX. Thus they would support Scalable OFDMA. Anyway, future Mobile WiMAX features are not deeply explained therefore information from Fixed WiMAX data sheet will be used.

- **Base Station**: Telsima's StarMAX 6400 Base Station is a Point to Multipoint (PMP) BS product designed to operate in the 3.30-3.40 GHz, 3.40-3.60GHz and 2.50-2.69 GHz spectrum and supports TDD as duplex method. The 802.16-2004 Standard compliant NLOS platform supports a strong suite of Quality of Service (QoS) features and multiple services. The product is capable of supporting 7 MHz, 6 MHz, 3.5 MHz and 3 MHz bandwidths, software configurable. Moreover, bandwidth can be configured form 1.5 to 14 MHz in 250 KHz steps on request. The maximum transmitted power is 30 dBm.
- **Subscriber Station**: StarMAX 2100 Subscriber Unit is 802.16-2004 Standard compliant. It operates in the 2.50-2.69 GHz, 3.30-3.40 GHz, 3.41-3.60 GHz RF bands. The product is capable of supporting 7 MHz, 6 MHz, 3.5 MHz and 3 MHz bandwidths, software configurable. Moreover, bandwidth can also be configured form 1.5 to 14 MHz in 250 KHz steps on request. 20 dBm is the maximum transmitted Power. There are three different Subscriber Station; 2130, 2140 and 2160, with different gains.

3.2.2 Comparison among products

A comparison in terms of the main performance is reported into two different tables. First one is filled for Base Stations and second one for Subscriber Stations. More features than required are described within the tables. It is important to distinguish between actual Mobile WiMAX devices and Fixed or coming Mobile WiMAX devices.

In those cases where Sensitivity is described in the data sheet for Fixed WiMAX, the value has been extrapolated as it is explained before. Thus, these values would theoretically be in accordance with the new 802.16e Standard.

Base Stations

In the case of Base Stations information is shown as: Firstly Company and Model are shown, afterwards all interesting and desired information for this thesis. Used WiMAX Standard will affect all features of the Base Stations.

About Frequency Bands; only TDD is certified by WiMAX Forum for the first profile (it will be further explained in the next point 4.3). It is the same about Bandwidth since it is depends of the new Mobile WiMAX profiles, and the Bandwidth would determinate the FFT size while within Fixed WiMAX only 256 OFDM is used. Gain and maximum transmitted power have a similar influence of the Fixed WiMAX. They do not use MIMO systems and other techniques to improve the connections. Thus, new devices will enhance the performance.

Table 3.4 Base Stations information

Producer	Airspan	Airspan	Alvarion	Axxcelera	Redline	Telsima
Model	MicroMAXe	MacroMAXe	BreezeMAX	ExcelMAX BS	RedMAX BS AN-100U	StarMAX 6400
WiMAX Standard	802.16e-2005	802.16e-2005	802.16-2004	802.16-2004, upgrade to 802.16e planned	802.16-2004	802.16-2004, future 802.16e
Frequency Bands	2.3GHz, 2.5GHz, 3.3GHz, 3.5GHz, 3.7GHz	2.3GHz, 2.5GHz	3.3GHz, 3.5GHz, 3.6GHz FDD	3.4GHz, 3.6GHz	3.3-3.5; 3.4-3.6; 3.6-3.8GHz	2.50-2.69, 3.40-3.60, 3.30-3.40GHz
Channel Size	20MHz, 2x10MHz, 10MHz, 5MHz	20MHz, 2x10MHz, 10MHz, 5MHz	3.5MHz, 1.75MHz	14MHz (opt), 7MHz, 3.5MHz, 1.75MHz	7MHz, 3.5MHz	7MHz, 6MHz, 3.5MHz, 3MHz (SW configurable)
Sensitivity	N.D.	N.D.	-99dBm for OFDMA 5MHz @ QPSK 1/2	-99dBm for OFDMA 5MHz @ QPSK 1/2	-97dBm for OFDMA 5MHz @ QPSK 1/2	-99dBm for OFDMA 5MHz @ QPSK 1/2
Antenna Gain	N.D.	N.D.	17 dBi typical	16dBi (60 degree), 14dBi (90 degree)	N.D.	N.D.
Tx. Power	Up to 2 x +36dBm	2x +40dBm	28dBm	+28.0 dBm (BPSK)	+23 dBm across all modulation/ coding levels	30 dBm

This table will not determine the used Frequency bands for the final calculations since it is required to follow ETSI Frequency usage plan, explained in the next point. It will condition the bandwidth as well as the frequency bands, although this thesis is focused in 5 and 10 MHz bandwidth.

At the same time maximum transmitted power for the Base Station is limited by the CPE to 20 dBm. Thus, Tx. Power information is only useful in order to know what the limit of the transmitter would be. On the other hand, at least, gain of Base Station for calculations can be accepted as approximately 16 dBi.

Mobile Stations

This second table has a very similar performance. It has exactly the same structure. And it also has parallel disadvantage since it is filled as well as before with Fixed WiMAX certified products, except of Airspan's and Alvarion's Subscriber Stations. Thus, for instance, Axxcelera and Redline Subscriber Station do not work in 2.5 GHz Frequency Band and 5 and 10 MHz Bandwidth. This can be noticed in the next table:

Table 3.5 Subscriber Station information

Producer	Airspan	Alvarion	Axxcelera	Redline	Telsima
Model	MiMAX USB	BreezeMAX (2300/2500/3500)	ExcelMAX Indoor CPE	RedMAX Subscriber Unit (SU-I)	StarMAX 2100
WiMAX Standard	802.16e-2005	802.16e-2005	802.16-2004	802.16-2004	802.16-2004, future 802.16e
Frequency Bands	2.3-2.4GHz, 2.496-2.69GHz,3.3-3.8GHz, 4.9-5.8GHz	2.3GHz, 2.5GHz, 3.5GHz	3.3-3.8 GHz	3.3-3.5; 3.4-3.6; and 3.6-3.8GHz	2.50-2.69GHz, 3.40-3.60GHz, 3.30-3.40GHz
Channel Size	10MHz, 8.75MHz, 7MHz, 5MHz	10MHz, 7MHz, 5MHz, 3.5MHz	7 MHz, 3.5MHz	3.5 MHz, 7MHz	7MHz, 6MHz, 3.5MHz, 3MHz (SW configurable)
Sensitivity	-100dBm for QPSK 1/2 OFDMA @ 5MHz	-98dBm for QPSK 1/2 OFDMA @ 5MHz	-92dBm for QPSK 1/2 OFDMA @ 5MHz	-97dBm for OFDMA 5MHz @ QPSK 1/2	-97dBm for OFDMA 5MHz @ QPSK 1/2
Antenna Gain	N.D.	Outdoor 14 dBi (2.5GHz) Indoor 7 dBi (2.5GHz)	10dBi (90º)	N.D.	2130: 10.5/8dBi 2140: 7/5dBi 2160: 16/14dBi
Tx. Power	up to 17dBm (4.9-5.8GHz) Up to 22dBm (others)	ND	24dBm	Up to +24 dBm	20dBm

In the previous table all sensitivities are described for Mobile WiMAX OFDMA. In the cases they were presented in the data sheets for Fixed WiMAX they have been extrapolated as it is explained before.

Although there are various characteristics shown for Base and Subscriber Stations only Tx. power and gain will be used for Base Stations and sensitivity and gain for Mobile Stations. This is due to evaluation is focused in downlink. In this situation Base Station is the transmitter and Mobile Station the receiver.

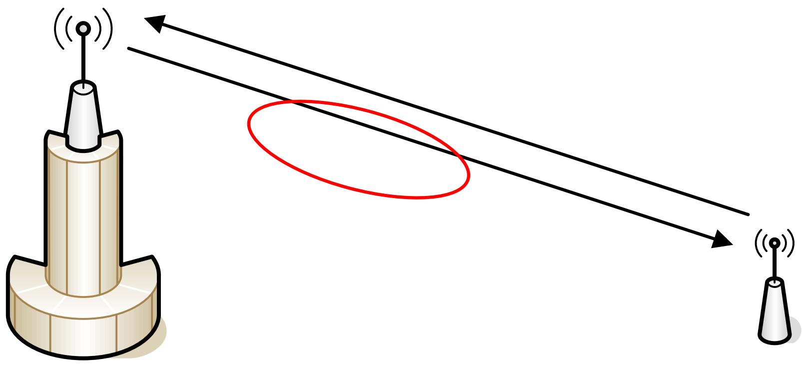

Figure 3.2: Uplink and Downlink

Since a lonely Subscriber Station possess sensitivity for Mobile WiMAX, it is difficult to decide the value of the sensitivity in accordance with 802.16e Standard. Thus, a value between estimated devices sensitivities and Standard requirements could be -94 dBm. And the gain would take a value of 8 dBi approximately since there is not so much information about gain in Mobile WiMAX devices and 8 dBi at the same time is more restrictive.

3.3 ETSI Frequency usage plan

WiMAX is designed to operate in the frequency range 2 to 66 GHz, however, most of interest is focusing on the 2 to 6 GHz range where LOS and NLOS scenarios are supported and in the new Standard 802.16e mobile operation is possible.

There are three main bands being considered for Mobile WiMAX implementation in Europe: 2.3 GHz and 3.5 GHz for licensed bands and 5.8 GHz for unlicensed bands. In addition, there are further bands which are being considered by the WiMAX forum: 2.5 GHz, 2.8 GHz and 3.3 GHz. The position with respect to the availability of this spectrum in Europe varies from country to country, since each country supervises the frequency spectrum. It makes it difficult to see how any European decision could be taken on an allocation.

As one can see, the IEEE 802.16 standard is quite flexible in terms of operation frequency, supporting both license and license-exempt bands. However, only licensed bands have been approved by the WiMAX Forum for the initial system profiles.

The WiMAX Forum has thus far defined five fixed certification profiles and fourteen mobility certification profiles (see Table). To date, there are two fixed WiMAX profiles against which equipment have been certified:

Table 3.6 Frequency usage plan

Frequency Band (Band index)	Channel Width	OFDM FFT size	Duplexing
Fixed WiMAX 802.16-2004			
3.5 GHz (1)	3.5 MHz	256	FDD
	3.5 MHz	256	TDD
	7 MHz	256	FDD
	7 MHz	256	TDD
5.8 GHz (2)	10 MHz	256	TDD
Mobile WiMAX 802.16e-2005			
2.3 - 2.4 GHz (1)	5 MHz	512	TDD
	8.75 MHz	1024	TDD
	10 MHz	1024	TDD
2.302 - 2.32 GHz 2.345 - 2.36 GHz (2)	5 MHz	512	TDD
	10 MHz	1024	TDD
2.496 - 2.69 GHz (3)	5 MHz	512	TDD
	10 MHz	1024	TDD
3.3 -3.4 GHz (4)	5 MHz	512	TDD
	7 MHz	1024	TDD
	10 MHz	1024	TDD
3.4 -3.8 GHz (5)	5 MHz	512	TDD
	7 MHz	1024	TDD
	10 MHz	1024	TDD

These are the frequency bands and channel bandwidths selected by the WiMAX Forum for the initial system profiles, which cover many of the worldwide spectrum allocations suitable for mobile WiMAX. Other frequency bands, channel bandwidths and FDD will be considered for future profiles based on specific market opportunities; 1.25 MHz (FFT size 128) and 20 MHz (FFT size 2048), thus as different combinations for frequency band and bandwidth.

3.4 Propagation models available

Propagation modeling is fundamental to the planning of Mobile WiMAX System and several propagation models have already been proposed for a wide range of scenarios of wireless communications. Since WiMAX system can operate in different frequencies this thesis is focused on propagation models that provides acceptable accuracy for LOS and NLOS scenarios and operation frequency up to 6GHz. At the same time it is significant the environment WiMAX is operating in. It will be distinguished two different environments: Urban and Suburban.

Thus, with these conditions, best fit propagation models are described. Last propagation model described, ECC-33 Path Loss Model, is not used for final calculations but it is explained since it is mentioned in many documents about wireless communications.

This propagation models are not specially described for WiMAX. Most of them are described for frequencies below 2.3 and 3.5 GHz.

3.4.1 Free Space Model

Assuming free-space propagation (without obstructions between the transmitter and receiver) path loss in dB, *PL*, is evaluated as.

$$PL(d) = 32.44 + 20\log_{10}(f) + 20\log_{10}(d) \qquad \textbf{(3.11)}$$

Where f is the working frequency in MHz and d represents the distance between the transmitter and receiver in Km. In this case LP is commonly considered L_0.

3.4.2 SUI Model

Stanford University developed channel models for the frequency below 11GHz which, in this case, are the aim of the researching. This model has been proposed for Broadband Wireless Access (BWA) systems operating under NLOS and LOS conditions. The SUI model is divided into three different types of terrain, known A, B and C. It considers in Type A the path loss associated with hilly terrain with moderate to heavy foliage environment that will result the maximum pass loss. In Type B model it considers either mostly flat terrains with moderate to heavy tree densities or hilly terrain with light tree densities. In Type C model it results the minimum path loss that associated with the flat terrain with the light tree densities. The path loss equation with correction factors is as follow [9]:

$$PL = A + 10\gamma \log_{10}\left(\frac{d}{d_0}\right) + X_f + X_h + s \qquad \text{for } d>d_0 \qquad \textbf{(3.12)}$$

Where d is the distance between transmitter and receiver, d_0 is the reference distance and s is the lognormally distributed factor which is used to account for the shadow fading owing to trees and other mess and the value is between 8.2dB and 10.6dB. The others parameters are defined as:

$$A = 20\log_{10}\left(\frac{4\pi d_0}{\lambda}\right) \qquad \text{with } \lambda = c/f \text{ in meters} \qquad \textbf{(3.13)}$$

$$\gamma = a - bh_{BS} + c/h_{BS} \qquad \textbf{(3.14)}$$

γ is the path loss exponent, the parameter h_{BS} is the subscriber station antenna height above ground and should be between 10 m and 80 m. The constants a, b and c depend on the terrain type, as presented in the table below:

Table 3.7 Numerical values for the SUI model parameters [9]

Model Parameter	Terrain A	Terrain B	Terrain C
a	4.6	4.0	3.6
b (m^{-1})	0.0075	0.0065	0.005
C (m)	12.6	17.1	20

The SUI model is originally competed to frequencies close to 6GHz and receiver antenna height between 10 m and 80 m. In order to surpass such limitations, correction factors are commonly used for the operating frequency:

$$X_f = 6.0\log_{10}(\frac{f}{2000}) \quad \textbf{(3.15)}$$

and the IEEE 802.16d channel model specifies a correction for the terminal antenna height,

$$X_h = -10.8\log_{10}(\frac{h_r}{2000}) \qquad \text{for Terrain types A and B} \quad \textbf{(3.16)}$$

$$= -20.0\log_{10}(\frac{h_r}{2000}) \qquad \text{for Terrain type C} \quad \textbf{(3.17)}$$

Where the frequency is in MHz and the height is in meters above the ground. The first expression seems to come from the AT&T measurements. The second is supposed to be the terminal height correction factor defined by Okumura. There seems to be an error here as the Okumura correction factor is:

$$X_h = -10\log_{10}(\frac{h_r}{3}) \qquad h_r < 3m \quad \textbf{(3.18)}$$

$$= -20\log_{10}(\frac{h_r}{3}) \qquad 10m > h_r > 3m \quad \textbf{(3.19)}$$

It can be shown that model needs corrections so that the reference distance increases with receiver height and it decreases with frequency. Then, calculating a new breakpoint distance:

$$PL = \begin{cases} A + 10\gamma\log\left(\frac{d}{d_0}\right) + X_f + X_h + s & for \quad d > d'_0 \\ 20\log\left(\frac{4\pi d}{\lambda}\right) + s & for \quad d \le d'_0 \end{cases} \quad \textbf{(3.20)}$$

Where;

$$A = 20\log_{10}\left(\frac{4\pi d'_0}{\lambda}\right) \quad \textbf{(3.21)}$$

$$d_0 = 100m \quad \textbf{(3.22)}$$

$$d'_0 = d_0 10^{-\left(\frac{X_h + X_f}{10\gamma}\right)} \qquad \textbf{(3.23)}$$

$$\gamma = a - bh_{BS} + {c}/{h_{BS}} \qquad \textbf{(3.24)}$$

d = distance between base and terminal

h_{BS} = height of base station

s = shadowing

and correction factors X_f and X_h are as described above.

Fading

A defining characteristic of the mobile wireless channel is the variations of the channel strength over time and frequency. The variations are denominated fading. Different classifications can be found depending on the book we are reading. In the case of [23] they can be divided into two types:

- Large-scale fading, due to the signal path loss as a function of distance and shadowing by big objects such as buildings and hills. This occurs when the mobile device moves through a distance of the order of the cell size, and is typically frequency independent.
- Small-scale fading, due to the constructive and destructive interference if there is multiple signal paths between the transmitter and receiver. This occurs at the spatial scale of the order of the carrier wavelength, and is frequency dependent.

According to [22] within Small-scale fading another division can be noticed. For one side the "multipath delay time spread leads to time dispersion and frequency selective fading". And the other effect would be produced by the Doppler since its "spread leads to frequency dispersion and time selective fading".

The most recognized classification for fading in the one which divides it into two types; Slow and fast fading. This division can be found in [24]. In this case it is considered that the major difficulties for a transmission within a city are caused by the fact that the most communication are affected by others via scattering of electromagnetic waves from surfaces or diffraction over and around buildings. These multiple propagation paths, generally defined multipath, have both slow and fast aspects:

- Slow fading appear due to the fact that most of the large reflectors and diffracting objects along the transmission path are remote from the terminal. The movement of the terminal relative to these remote objects is small; as consequence, the corresponding propagation changes are slow. The statistical variation of these mean losses due to the variation of intervening terrain, vegetation, etc., is modeled as a lognormal distribution for terrestrial applications. The slow-fading process is also referred to as shadowing or lognormal fading.

- Fast fading is the fast variation of signal levels when the user station moves short distances. Fast fading is due to the reflections of local objects and the motion of the mobile device relative to those objects. Thus, the received signal is the sum of a certain number of signals reflected from local surfaces, these signals can be summed in a constructive or destructive manner, depending on their relative phase relationships. The resulting phase relationships are dependent on the relative path lengths to the close objects, and they can change with significance over short distances. In the case of the figure 3.3 S_1 and S_2 are summed in a constructive manner at T_1 however in a destructive manner at T_2. Particularly, the phase relationships depend on the speed of the motion and the frequency of transmission.

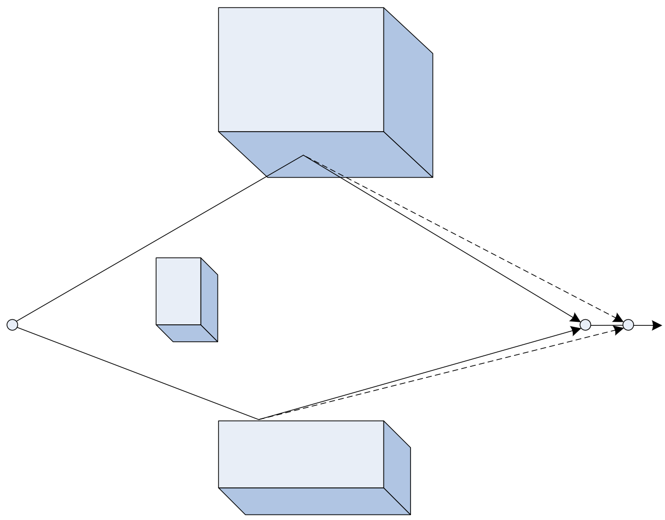

Figure 3.3: Constructive and destructive interference

There are many fading models for representing the distribution of the attenuation: Nakagami, Weibull, Rayleigh, Rician, Dispersive fading model and lognormal shadowing fading.

In the case of SUI propagation model the fading effect is assumed as lognormal shadowing fading and its expression is given by Okumura as:

$$\sigma = 0.65[\log f]^2 - 1.3\log f + A \tag{3.25}$$

Transmitter

with f in MHz,

A = 5.2dB (urban) or 6.6dB (suburban)

3.4.3 COST-231 Hata

The Hata model is an empirical approach of the graphical path loss data provided by Okumura and the operating frequency is between 150MHz and 1500MHz. The predictions of Hata model is closely related to the Okumura model, as long as distance exceeds 1 km. Therefore, this model is well suited for the large cell mobile systems (cell radius above 1 km, but it provides good results only for d > 5 km).

COST-231 Hata model was devised as an extension to the Hata-Okumura model. This model is purported to be used in the frequency band from 500MHz to 2000MHz. It is restricted to large and small macro-cells. Four parameters are used for estimation of the propagation loss by Hata´s well-known model: frequency f

(MHz), distance d (Km), base station height h_b (m) and the height of the mobile antenna h_m (m). COST-231 Hata model can be written as follow:

$$PL = 46.3 + 33.9\log_{10}(f) - 13.82\log_{10}(h_b) - ah_m + (44.9 - 6.55\log_{10}(h_b))\log_{10} d + C_m \quad \textbf{(3.26)}$$

Where the parameter C_m is defined as 0dB for medium sized city and suburban centres with medium tree density and 3dB for metropolitan centres. The parameter ah_m is defined for urban environments as follow:

$$ah_m = 3.20(\log_{10}(11.75h_m))^2 - 4.97 \qquad \text{for } f > 400\text{MHz} \quad \textbf{(3.27)}$$

and for suburban or rural (flat) environments

$$ah_m = (1.1\log_{10} f - 0.7)h_m - (1.56\log_{10} f - 0.8) \quad \textbf{(3.28)}$$

This factor is a correction factor for effective mobile antenna height, which depends on the size on the coverage area. The validity domain of COST-231 Hata model is:

Table 3.8 COST-231 Hata limitations

Frequency (f)	1500-2000 MHz
Base Station Height (h_{BS})	30-200 m
Mobile Height (h_{MT})	1-10 m
Distance (d)	1-20 km

3.4.4 COST-231 Walfisch-Ikegami model

COST-231 Walfisch-Ikegami model allows an improvement of the estimation of the path loss in suburban and urban environments where buildings are quasi-uniform, by considering additional environment data: height of building h_{roof}, width of roads w, buildings separation, b, and road orientation with respect to the direct radio path, γ. Furthermore, this model is valid when base station antenna is situated below rooftop level. It has been obtained from [21]:

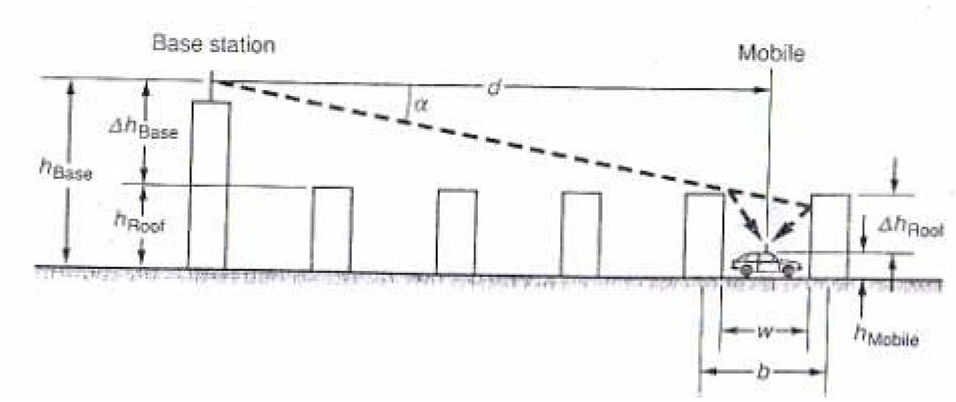

Figure 3.4: COST-231 W-I environment

In addition, it discerns between LOS and NLOS conditions. For the LOS case, the propagation loss is expressed as follow:

$$LP = 42.6 + 26\log d[km] + 20\log f[MHz] \qquad d \geq 20m \tag{3.29}$$

Under NLOS, the path loss is evaluated from:

$$LP = \begin{cases} L_0 + L_{rts} + L_{msd} & for\ L_{rts} + L_{msd} \geq 0 \\ L_0 & for\ L_{rts} + L_{msd} \leq 0 \end{cases} \tag{3.30}$$

where L_0 is the free space loss, L_{msd} is the multiple screen diffraction loss. The L_{rst} describes the coupling of the wave propagating along the multiple-screen path into the street where the mobile station is located:

$$L_{rts} = -16.9 - 10\log(w_{[m]}) + 20\log f_{[MHz]} + 20\log \Delta h_{MT[m]} + L_{Ori} \tag{3.31}$$

where L_{Ori} is an empirical correction factor, obtained from a few experimental measurements:

$$L_{Ori} = \begin{cases} -10 + 0.354\varphi & for\ 0^\circ \leq \varphi < 35^\circ \\ 2.5 - 0.075(\varphi - 35) & for\ 35^\circ \leq \varphi < 55^\circ \\ 4.0 - 0.114(\varphi - 55) & for\ 55^\circ \leq \varphi < 90^\circ \end{cases} \tag{3.32}$$

where j is the angle between incidences coming from base station and road , in degrees shown in following figure:

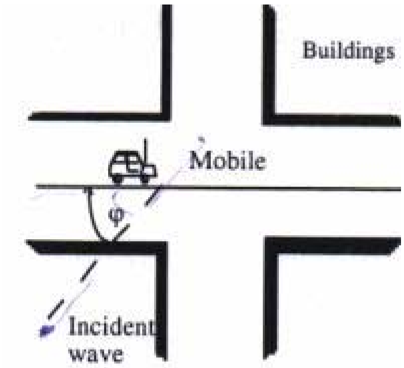

Figure 3.5: Angle for Base Station

and,

$$\Delta h_{MT} = h_{Roof} - h_{MT} \tag{3.33}$$

The multiple screen diffraction loss, L_{msd}, is defined as:

$$L_{msd} = L_{bsb} + K_a + k_d \log d_{[km]} + k_f \log f_{[MHz]} - 9\log b_{[m]} \tag{3.34}$$

where:

$$L_{bsb} = \begin{cases} -18\log(1+\Delta h_{BS[m]}) & for \;\; h_{BS} > h_{Roof} \\ 0 & for \;\; h_{BS} \le h_{Roof} \end{cases} \tag{3.35}$$

$$K_a = \begin{cases} 54 & for \;\; h_{BS} > h_{Roof} \\ 54 - 0.8\Delta h_{BS} & for \;\; d \ge 0.5\,km \;\; and \;\; h_{BS} \le h_{Roof} \\ 54 - 0.8\Delta h_{BS}\dfrac{d_{[km]}}{0.5} & for \;\; d < 0.5\,km \;\; and \;\; h_{BS} \le h_{Roof} \end{cases} \tag{3.36}$$

$$k_d = \begin{cases} 18 & for \;\; h_{BS} > h_{Roof} \\ 18 - 15\dfrac{\Delta h_{BS}}{h_{Roof}} & for \;\; h_{BS} \le h_{Roof} \end{cases} \tag{3.37}$$

$$k_f = -4 + \begin{cases} 0.7\left(\dfrac{f_{[MHz]}}{925} - 1\right) & for\,medium\,sized\;city\;and\;suburban\;centres \\ & with\;\;medium\;\;tree\;\;density \\ 1.5\left(\dfrac{f_{[MHz]}}{925} - 1\right) & for\,metropolitan\,centres \end{cases} \tag{3.38}$$

with:

$$\Delta h_{BS} = h_{BS} - h_{Roof} \tag{3.39}$$

The term k_a denotes the increase of the path loss for base station antennas below the rooftops of adjacent buildings. The terms k_d and k_f control the dependence of the multi screen diffraction loss versus distance and radio frequency.

Restrictions of the model are given as follow:

Table 3.9 COST-231 Walfisch-ikegami model limitations

Frequency (f)	800-2000 MHz
Base Station Height (h_{BS})	4-50 m
Mobile Height (h_{MT})	1-3 m
Distance (d)	0.02-5 km

In case of that data on the structure of buildings and roads are not available, following values could be taken as default.

h_{Roof}= 3m{number of floors}+{roof-height}

roof-height =3 m for pitched or 0 m for flat

b=20...........50 m, w=b/2, φ=90º

3.4.5 ECC-33 Path Loss Model

The ECC-33 path loss model, which is developed by Electronic Communication Committee, is extrapolated from the original measurements by Okumura, which were gathered in the suburban areas of Tokyo. The authors divided the urban areas into two categories; 'large city' and 'medium city' and it classifies the suburban areas into 'open' and 'quasi-open' areas. A typical European city is quite different from the Tokyo´s environment. It can be therefore categorized as a 'medium city'. The basic path loss is as follow:

$$PL = A_{fs} + A_{bm} - G_b - G_r \tag{3.40}$$

Where A_{fs}, A_{bm}, G_b and G_r are the Free space propagation loss, the basic median loss, the bass station height gain factor and the mobile station height gain factor respectively, and they have the values:

$$A_{fs} = 92.4 + 20\log_{10} d + 20\log_{10} f \tag{3.41}$$

$$A_{bm} = 20.41 + 9.83\log_{10} d + 7.894\log_{10} f + 9.56(\log_{10} f)^2 \tag{3.42}$$

$$G_b = \log_{10}(h_b/200)\{13.958 + 5.8[\log_{10} d]^2\} \tag{3.43}$$

$$G_r = [42.57 + 13.7\log_{10} f][\log_{10} h_m - 0.585] \tag{3.44}$$

Where, f is the frequency in GHz, d is the distance between the base station and the mobile station, h_b is the Base station antenna height in meters and h_m is the Mobile station antenna height in meters.

4. CALCULATION

Preamble point is essential for comprehending the following calculations. As it has been mentioned before, this thesis is focused in 5 MHz and 10 MHz Bandwidth, since they are both the most important bands for Mobile WiMAX. At the same time WiMAX forum has only accept the licensed band of 2.3 GHz yet and the other important central frequency will be 3.5 GHz. Therefore, in accordance with current regulatory rules, the resulting scenarios are described in the next table, where 2.3 GHz and 3.5 GHz are working into Urban and Suburban environments:

Table 4.1 Outdoor Scenarios

Scenario	Description	Parameters
A	Licensed Bands Suburban and Urban Environment	BW: 5 and 10 MHz F_C: 2.3 GHz Modulations: QPSK and 64-QAM Coding rates: 1/2, 2/3 and 3/4 Sensitivity: -94 dBm Tx Power: 20 dBm Antennas gain: 16 dBi BS and 10 dBi MS
B	Licensed Bands Suburban and Urban Environment	BW: 5 and 10 MHz F_C: 3.5 GHz Modulations: QPSK and 64-QAM Coding rates: 1/2, 2/3 and 3/4 Sensitivity: -94 dBm Tx Power: 20 dBm Antennas gain: 16 dBi BS and 6 dBi MS

It must be reminded that the sensitivity written above is for a 5 MHz bandwidth and QPSK 1/2 modulation, which mean that it is the best possible sensitivity, that means best coverage radius but lowest throughput.

Sensitivity, transmitted power and antennas gains have been chosen in order to point 3.2 where features from Base and Subscriber Stations where explained. Within this context, Mobile Station gain is different for 2.3 GHz and 3.5 GHz environments in order to perform in a better manner the real products and surroundings effects, both are around the value determined from Products, 8 dBi. Anyway, it is difficult to simulate conditions when the Mobile WiMAX products have not been certified yet, thus, this thesis contributes an orientation about Mobile WiMAX performance.

It is primordial to notice that the environment will affect the coverage and as consequence the maximum data rate since it is related with the modulation technique. Depending of the coverage area different modulation techniques can be used. This aspect can be observed in the next figure:

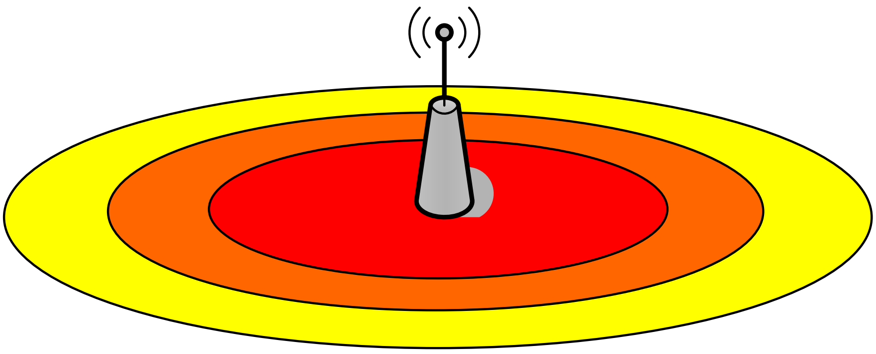

Figure 4.1: Adaptive Modulation in WiMAX technology

The shortest coverage area is for 64-QAM however, this modulation technique achieves the highest data rate. On the other hand QPSK has the widest radius of coverage with the lowest data rate.

4.1 Coverage Prediction Evaluation

For calculating the coverage radius excel has been used. Within a excel sheet all formulas from all propagation models have been written in order to find the correct value of distance (*d*).

$$P_r = P_t + G_t - PL + G_r \tag{4.1}$$

From the precious formula, as minimum required received power, both gains and transmitted power are already know, possible value for Path Loss can be found, as follow.

QPSK 16-QAM 64-QAM

$$PL = P_t - P_r + G_t + G_r \qquad \textbf{(4.2)}$$

Thus, for instance, the maximum value for Path Loss would be:

$$PL = 20dBm + 94dBm + 10dBi + 16dBi = 140dB \qquad \textbf{(4.3)}$$

It must be noticed that the result is in dB because P_r is with a symbol minus (-). This means that transmitted and received power in a logarithmic form would be dividing each other, as consequence the both dBm would transform to dB. So, this total Path Loss is equalized with every Propagation Model, hence a formula can be achieved. Solving properly this formula, the maximum coverage radius can be obtained for each different Propagation Model.

The impact of Bandwidth on coverage is in accordance to OFDMA characteristics. Actually, by increasing BW and corresponding number of used sub-carriers, the antenna's sensitivity worsens in this manner (complete formula in 4.1.1):

$$10\log\left(\frac{F_S x N_{used}}{N_{FFT}}\right) \qquad with \quad F_S = floor\left(nBW/8000\right)8000 \qquad \textbf{(4.4)}$$

Since the thesis is focused in 5 and 10 MHz Bandwidth, it can be easily noticed that sampling frequency is double in 10 MHz with respect of 5 MHz (n=28/25 in both cases), therefore the difference between these two bandwidths is 3dB.

On the other hand the effect of using different modulation techniques on coverage prediction is greater than the bandwidth's one. The influence of modulation is completely related with the requirements of SNR, these values are written in Table 3.1. Thus, the different between the worst (64-QAM at 3/4) and the best case (QPSK at 1/2) is 15 dB. Taken QPSK 1/2 as 0 dB, QPSK 3/4 would be 3 dB and on the other side 64-QAM 2/3 and 64-QAM 3/4 would be 13 and 15 dB respectively.

For a more rigorous study of the radius coverage, as mentioned before, the results are shown in the next order; Since SUI propagation model has three types of terrain, firstly type C, B and last one type A because it is been used for urban environment therefore it will obtain the worst results. On the other hand, both COST-231 models consider urban and suburban environments therefore formulas will be distinguished in the results.

At the same time Free Space propagation model is used in both Scenarios in order to compare easily values with the theoretical maximum coverage. Thus, the influence of varied determining factors can be assessed.

There are various important values for calculations. They are related with each propagation model, different references for each one. Therefore, within this context, the following values have been taken:

- Base Station height is 30 meters since it is more or less the height of 5 levels building plus the antenna height, 20 meters for the building and 10 for Antenna. Mobile Station is declared as 2 meters.
- Reference distance, as it is taken in most of propagation models, is 100 meters.
- Building separation and width of roads have been chosen in accordance with COST-231 Walfisch-Ikegami model recommendations (at the final of point 4.4.4). Thus, building separation has been set to 25 meters and as consequence width if roads are 12.5 meters. As it is mentioned in the recommendations as well the road orientation is taken as 90 degrees.

Anyway, values can be easily changed since they are written in excel. Thus, it could be adapted to various different environments.

4.1.1 Scenario A

With all the explanations about steps followed to calculate the coverage radius, it is clear how results will be obtained. Then, with the mentioned values for the sensitivity, gains and transmitted power, the coverage for Scenario A results as follow:

Table 4.2 Estimated coverage for 5 MHz into Scenario A

Propagation Model	5 MHz			
	QPSK		64-QAM	
	1/2	3/4	2/3	3/4
Free Space	103,82	73,50	23.24	18,46
SUI C	1,59	1,35	0,77	0,69
SUI B	1,35	1,15	0,68	0,61
SUI A	1,07	0,93	0,57	0,52
COST-231 Hata Sub	1,12	0,92	0,48	0,42
COST-231 Hata Urb	0,89	0,73	0,38	0,33
COST-231 W-I Sub	0,87	0,73	0,40	0,35
COST-231 W-I Urb	0,58	0,49	0,26	0,23

This table summarizes the coverage radius for 5 MHz Bandwidth. It can be noticed the difference among different path loss models, where Free Space model is shown in order to collate with the others more realistic models.

There is an enormous difference between Free Space model and others models. Logically, Free Space model achieves higher coverage radius because no parameters are reckoned. Only frequency affects the result. This phenomenon is repeated in every scenario and bandwidths.

Table 4.3 Estimated coverage for 10 MHz into Scenario A

Propagation Model	10 MHz			
	QPSK		64-QAM	
	1/2	3/4	2/3	3/4
Free Space	73,50	52,03	16,45	13,07
SUI C	1,35	1,14	0,65	0,58
SUI B	1,15	0,98	0,58	0,52
SUI A	0,93	0,80	0,50	0,45
COST-231 Hata Sub	0,92	0,76	0,39	0,34
COST-231 Hata Urb	0,73	0,60	0,31	0,27
COST-231 W-I Sub	0,73	0,61	0,33	0,29
COST-231 W-I Urb	0,49	0,40	0,22	0,20

In this second table, the difference with previous values is solely the effect of 3 dB, previously mentioned. The difference is approximately around 20% (mostly a bit less than 20%) wider the coverage for 5 MHz than for 10 MHz.

Finally a graphic with different coverage radius for various path loss values is shown in order to provide information for any device, with its respectively sensitivity, gain or transmitted power, at the same time it can be used to compare with better devices (higher gain or transmitted power as well as better sensitivity). Free Space propagation model is not shown since its values are much greater than in other models, and it can be considered solely as an ideal case.

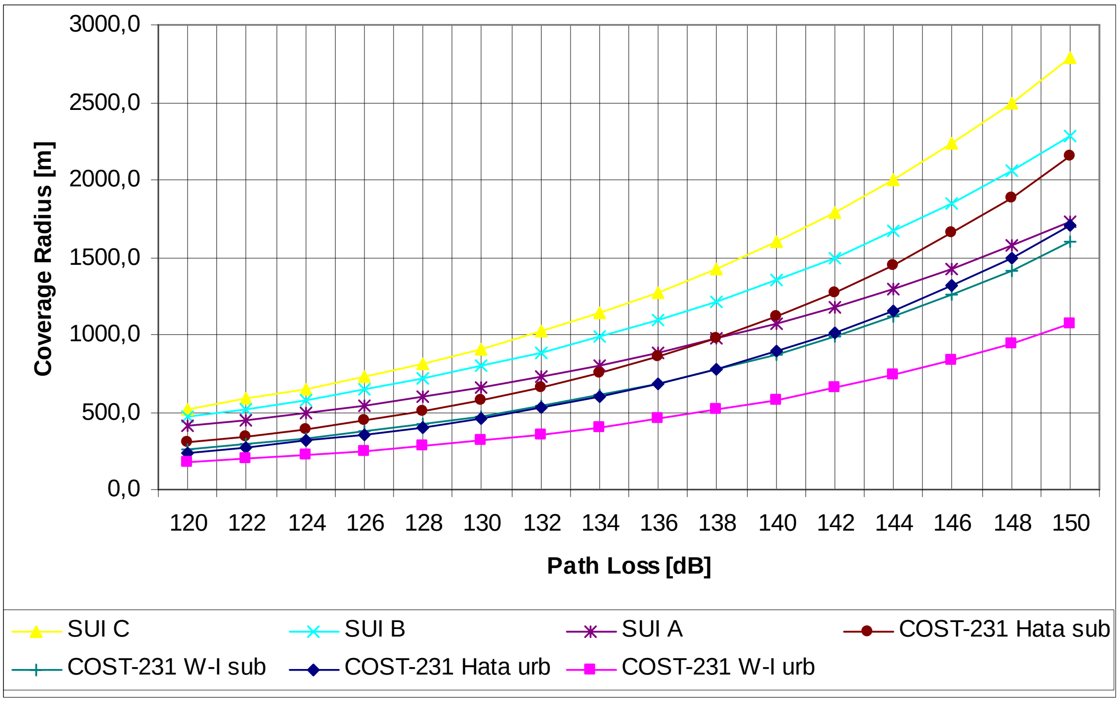

Figure 4.2: Coverage Radius for scenario A

Observing Figure 4.2, it can be noticed that SUI A and COST-231 Hata Suburban are crossed somewhere around 137 dB. For upper Path Loss values COST-231 Hata Suburban will obtain better coverage radius and vice versa. COST-231 W-I Suburban and COST-231 Hata Urban have similar performance, however, in this case, both lines are very together within low path loss and after 140 dB it looks they are going to get separated more and more, at a low rhythm.

4.1.2 Scenario B

Same tables and graphic are shown in this Scenario B. Similar results can be observed, although as higher is the central as worse are the coverage radius, therefore this environment, because of the central frequency's influence, is more adverse for coverage radius the resulting values decrease comparing with Scenario A. At the same time, within Scenario B, the Mobile Station has a gain of 6 dB instead of those 10 dB used in the Mobile Station for Scenario A.

Then the total different values are shown in the next table for 5 MHz Bandwidth.

Table 4.4 Estimated coverage for 5 MHz into Scenario B

Propagation Model	5 MHz			
	QPSK		64-QAM	
	1/2	3/4	2/3	3/4
Free Space	65,50	46,37	14,66	11,65
SUI C	1,27	1,08	0,62	0,55
SUI B	1,09	0,93	0,55	0,50
SUI A	0,88	0,76	0,47	0,43
COST-231 Hata Sub	0,86	0,71	0,37	0,32
COST-231 Hata Urb	0,68	0,56	0,29	0,26
COST-231 W-I Sub	0,68	0,57	0,31	0,28
COST-231 W-I Urb	0,46	0,38	0,21	0,18

Table 4.4 contains the results for 10 MHz bandwidth with 3.5 GHz central frequency. In fact, this table contains worst results for coverage radius.

Table 4.5 Estimated coverage for 10 MHz into Scenario B

Propagation Model	10 MHz			
	QPSK		64-QAM	
	1/2	3/4	2/3	3/4
Free Space	46,37	32,83	10,38	8,25
SUI C	1,08	0,91	0,52	0,47
SUI B	0,93	0,80	0,47	0,42
SUI A	0,76	0,76	0,41	0,37
COST-231 Hata Sub	0,71	0,58	0,30	0,27
COST-231 Hata Urb	0,56	0,46	0,24	0,21
COST-231 W-I Sub	0,57	0,48	0,26	0,23
COST-231 W-I Urb	0,38	0,32	0,17	0,15

In this second table, the difference with previous values is solely the effect of 3 dB, as well as before. And it can be also noticed that the difference is also approximately around 20% (in this cases a bit more than 20% in some cases) wider the coverage for 5 MHz than for 10 MHz.

Finally a graphic with every propagation model is shown as before in order to provide information for any device, with its respectively sensitivity, gain or transmitted power, at the same time it can be used to compare with better devices (higher gain or transmitted power as well as better sensitivity). Free Space propagation model is again not shown since its values are also much greater than in other models, and it can be considered solely as an ideal case.

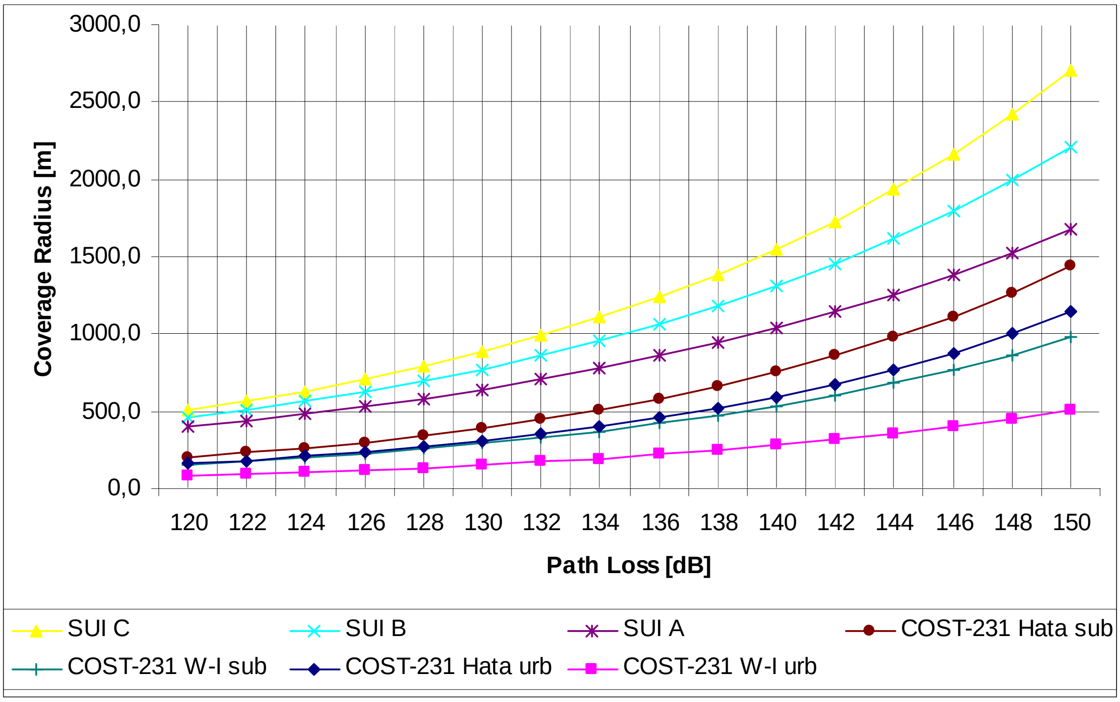

Figure 4.3: Coverage Radius for scenario B

In this table it can be noticed that higher central frequency affects especially both COST-231 propagation model. Coverage radius is lower for every propagation model, for SUI models (all types) this difference is very small however for COST-231 propagation models this difference can reach 100%.

This is the case of COST-231 W-I for urban terrain. For a Path Loss of 140 dB, within 3.5 GHz environment, 279 meters is resulted from the calculations as the coverage radius. If it is compared with 582 meters resulted within 2.3 GHz environment, the increase is 108%.

4.2 Theoretical Maximum throughput

Once, in accordance with sensitivity, antenna gains and path loss, that the Mobile Station has established a connection with the Base Station with one of the modulation techniques, the achieved maximum data rate can be calculated.

For this goal, the values of the most relevant system parameters are defined, in accordance to the IEEE 802.16e Standard.

Table 4.6 OFDMA parameters according with 802.16e-2005 Standard

Parameter	5 MHZ		10 MHZ	
	Downlink	Uplink	Downlink	Uplink
N_{used}	420=360d+60p	408=272d+136p	840=720d+120p	840=560d+280p
N_{FFT}	512		1024	
b_m	2 (QPSK), 4 (16-QAM) and 6 (64-QAM)			
c_r	1/2, 2/3 and 3/4			
G	1/4, 1/8, 1/16 and 1/32			
n	8/7 for BW a multiple of 1.75 MHz 28/25 for BW a multiple of 1.25, 1.5, 2 or 2.75 MHz 8/7 for rest of cases			

In the table above, the number of used sub-carriers (N_{used}) is divided into two groups; data sub-carriers and pilot sub-carriers, denoted with d and p respectively. It is very important distinguishing this number since the total (data plus pilot sub-carriers) is used for solving the value of bandwidth influence in sensitivity (described above, 5.1) and calculation for the theoretical maximum data rate use only the number of data sub-carriers in order to be stricter with acquired results.

On the same path of getting a strict value in calculations, data rate has been decreased by a factor of 9/8 and 44/42, this means that final result of calculations are multiplied by 8/9 and 42/44. These factors are related with Cyclic Prefix and frame structure respectively.

Therefore, the maximum theoretical throughput has been calculated as follow: first of all sub-carrier spacing (Δf) is calculated from sampling frequency (F_S) by using formulas from additional information (3.1.2):

$$\Delta f = 10937.5\,Hz \quad \textbf{(4.5)}$$

then, symbol duration can be obtained as the sum of useful symbol interval ($T_b=1/\Delta f$) and guard interval (T_g). In this thesis, guard interval has a value of 1/8. Hence,

$$T_S = T_b + T_g = (G+1)T_b = 102.9\,\mu s \quad \textbf{(4.6)}$$

this value is used for both bandwidths. In accordance of preamble, the inverse of this number must by multiplied by the N_{used} (in this case only data sub-carriers), number of bits per modulation symbol (b_m, depending on the modulation technique) and the coding rate, c_r.

In this context and reminding that number of data sub-carriers is: 360 for downlink and 272 for uplink in a bandwidth of 5 MHz and 720 for downlink and 560 for uplink in 10 MHZ. The obtained result of these calculations is:

Table 4.7 Estimated Maximum Data rate in Mbps

Transfer Rate	5 MHz				10 MHz			
	QPSK		64-QAM		QPSK		64-QAM	
	1/2	3/4	2/3	3/4	1/2	3/4	2/3	3/4
Downlink (MHz)	2,91	4,36	11,64	13,09	5,82	8,73	23,27	26,18
Uplink (MHz)	2,20	3,30	8,79	9,89	4,52	6,79	18,10	20,36

Thus the maximum downlink and uplink date rate are 26 and 20 Mbps respectively, which both are achieved for 10 MHz channel bandwidth, 64-QAM modulation with 3/4 coding rate. In this case, coverage radius is between 580 and 270 meters (depending on the propagation model) for Suburban environments and between 410 and 150 meters for urban environments.

Comparing maximum throughput and coverage radius, it can be perceived that operation in 5 MHz bandwidth provides better coverage but with lower throughput than in 10 MHz bandwidth. Thus, for maximum coverage radius (with 5 MHz Bandwidth) 2.9 and 2.2 Mbps will be achieved at least for Downlink and Uplink respectively.

Then, C Area shall contain the maximum data rate, with every Mobile Station using 64-QAM modulation technique. The maximum data rate for set of Mobile Station which uses 64-QAM is call denominated C (Mbps). And the name of the data rate for Mobile Station placed within A Area is called consequently A (Mbps).

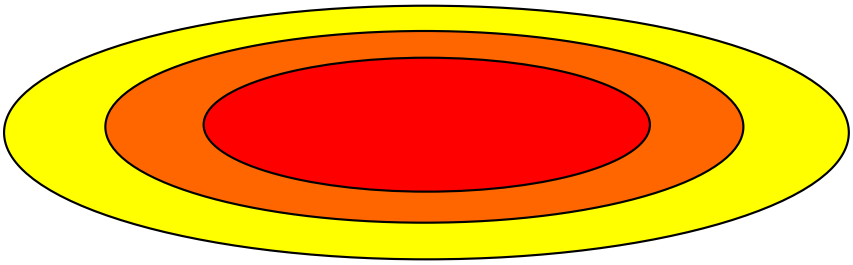

Figure 4.4: Different modulation techniques areas

In this manner, Mobile Station placed into B Area will reach a data rate which comply this condition:

A B C

$$A(Mbps) < B(Mbps) < C(Mbps) \quad \textbf{(4.7)}$$

5. MEASUREMENTS TAKEN

5.1 Environment

In order to compare theoretical calculations with real values some measurements have been taken around the Base Station which is placed in the roof of Electrical Faculty within Maslak Campus (Istanbul Technical University).

Figure 5.1: Electrical Faculty in Maslak Campus

Places around Campus have been chosen with the help of the program "Radio Mobile" and "Google Earth". Program "Radio Mobile" is a tool used to predict the performance of a radio system. It uses digital terrain elevation data for automatic extraction of path profile between a transmitter and a receiver.

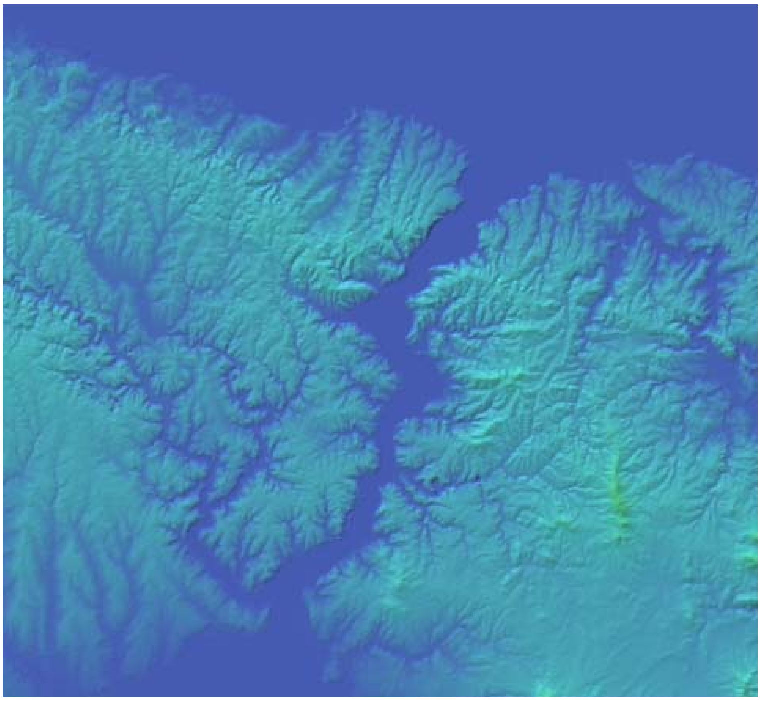

Figure 5.2: Elevation Map of Istanbul and Bosphorus

Above Elevation map of Istanbul and surroundings is shown. With the help of this map and by introducing all the information about the transmitter (Base Station) and receiver (Subscriber Station) places for measurements have been chosen. This information includes antennas height, gains, transmitted power, etc. Thus, next map is showing the final possible areas of coverage.

Figure 5.3: Coverage areas for testing

In the previous map, points within each area have been already shown in order to avoid adding many different maps with little information. These points have been selected because of the situation; high part of the terrain, no buildings in front or other reasons. Always, in order to get the best link quality. However in the Area 4, even with a good position, it was impossible to access to the network, neither in Area 5.

5.2 Used devices

BreezeMAX family from Alvarion has been used for these measurements. Thus, omnidirectional antenna, Access Unit ODU (OutDoor Unit) and Micro Base Station have been used for the Base Station. On the other side, PRO CPE ODU and Broadband Data CPE have been utilized for the Subscriber Station. All of these products and the final WiMAX Network can be seen in the next figure.

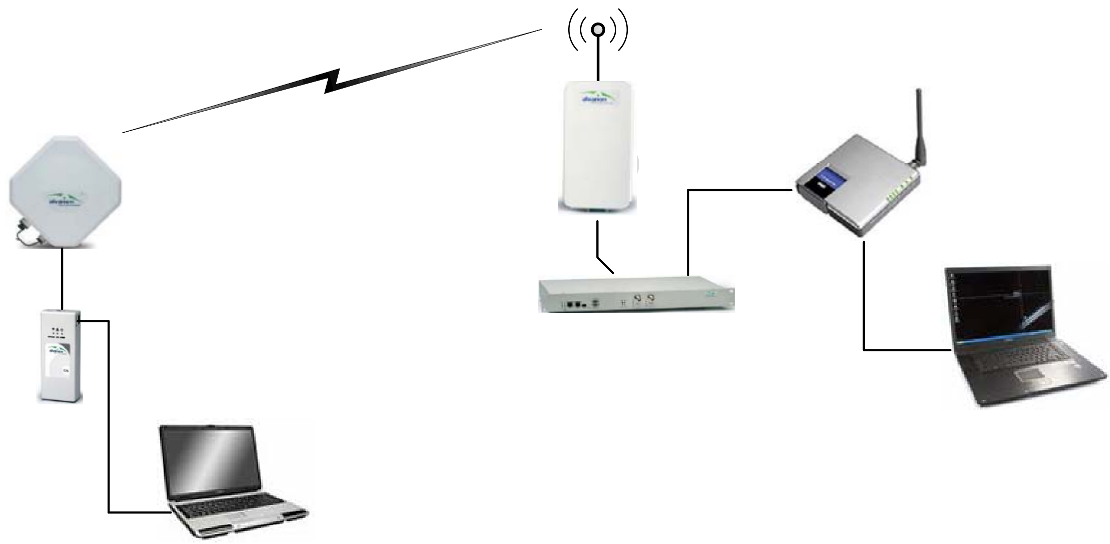

Figure 5.4: WiMAX Network

In the previous figure, it can be noticed that more devices have been utilized such as: Router Linksys, Toshiba laptop (client) and Asus laptop (server).

The WiMAX Network is operating in the frequency of 3.7 GHz and a bandwidth of 3.5 MHz with TDMA FDD as Radio Access Method. In the case of FDD, the bandwidth for Uplink and Downlink are half of the total bandwidth and as consequence the data rate for UL and DL should be the same. In this case, only Uplink has been tested.

5.3 Measurements

Once the WiMAX Network has been completely described, the followed procedure for testing the connection can be explained. In this case Iperf has been used in order to measure the data rate between the Base Station (Server) and Subscriber Station (client). Iperf was developed by NLANR/DAST as a modern alternative for measuring maximum TCP and UDP bandwidth performance. Iperf allows the tuning of various parameters and UDP characteristics. However, in this case, only TCP connections have been tested.

The commands for Server and Client are a bit different, although in these measurements very basic commands have been utilized. Then, hence, following commands are:

iperf –s –i1 for server

iperf –c 1.1.1.5 –i1 –t10 for client

-s and –c are respectively the notation for server and client. –i1 means seconds interval between periodic bandwidth reports, in this case one second. 1.1.1.5 is the IP address of the server and –t10 is the time the test is running, in this case ten seconds.

Thus, the realized test was running only during 10 seconds however more than one test for each point has been done; two tests for Area 1 and 3 and three tests for Area 2. At the same time Iperf was measuring the Bandwidth, the Base Station Program installed in the Laptop acting as server was collecting all the information about the Link. This includes SNR UL and DL, RSSI UL and DL and used Modulation technique for UL and DL as well.

The weather conditions were not the most suitable for the objective but they had to be taken that day. Wind was 10 Km/h, decreasing during the day. Temperature was between 8 and 5 Celsius degrees and the humidity was around 76%.

It should be reminded that the connection is FDD; thus, the bandwidth is divided symmetrically for Uplink and Downlink. In this case only Uplink is tested since is the client which is sending packets to the server. These packets have a size of 8 kbits.

It is also important to remind that the multiplexing technique is OFDM instead of OFDMA used in Mobile WiMAX. In this case the number of FFT is fixed and equal to 256, where the number of used sub-carriers is 192.

The last line of every following table contains the results of measurements which were taken in May of 2007 with much better weather conditions and clear sky. These conditions were:

temperature: 17º - 24º

humidity: 20 % - 32 %

wind speed: 10 – 40 km/h

These measurements were taken by Istanbul Technical University students who were working for an Undergraduate Thesis. These theses can be found in the main Library and the results were provided by the Advisor. In this case, both links were tested; Uplink and Downlink by performing a full duplex TCP test. Also Iperf was used in these tests but with different commands, thus, it was possible to test the link with various configurations. Data Rates are an approximation of the average that it would be obtained from all the acquired values.

Point Area 1

Area 1 is located the closest of all of them to the Campus and as consequence to the Base Station. The exact distance for the Base Station to the Subscriber Station when the measures were taken was 2.6Km. These measurements were taken in the middle of the street with many cars passing around and likely without line of sight. This aspect was especially due to it was a raining day with fog.

Table 5.1 Measurements results for Area 1

SNR UL (dB)	SNR DL (dB)	RSSI UL (dBm)	RSSI DL (dBm)	Modulation UL	Modulation DL	Data Rate (Kbps)
18,6	20	-86,8	-83	BPSK 3/4	BPSK 1/2	1920
21,1	20	-83,9	-83	BPSK 3/4	BPSK 1/2	1830

17	***20,4***	***-87,1***	***-82,3***	***QAM-16 3/4 - QAM-16 1/2***	***QAM-64 3/4 - QAM-16 3/4***	***N.D.***

In the previous table it was be noticed that ratios for signal and noise are quite high and as consequence the Uplink is working with BPSK 3/4 Modulation technique, which in these measurements is the highest Modulation technique achieved.

The measurement from May is higher in the Modulation Technique but almost equal in SNR and RSSI levels, this is mainly because of the humidity which was quite high (73%) that day of May. However there is not information about the Data Rate for that day.

Point Area 2

In this case, this area is located in the Asian side of the city, with the Bosphorus in the middle. A very suitable place was got in this case, with possible line of sight with the Base Station. It was only “possible” because as it is mentioned before the day was not very clear and there was fog.

The distance between the Base Station and Subscriber Station was around 4.17Km. And there were not high buildings around, cars neither.

Table 5.2 Measurements results for Area 2

SNR UL (dB)	SNR DL (dB)	RSSI UL (dBm)	RSSI DL (dBm)	Modulation UL	Modulation DL	Data Rate (Kbps)
5,4	9	98,8	93	BPSK 1/2	QPSK 1/2	870
8,1	11	96,5	91	BPSK 3/4	BPSK 1/2	1660
6	3	98,7	97	BPSK 1/2	BPSK 1/2	869
7,8	***13,9***	***-95,9***	***88,8***	***QPSK 3/4***	***QAM-16 3/4 - QAM-16 1/2***	***1800***

Three measurements were taken. Fortunately in one of them BPSK 3/4 Modulation technique were achieved and it can be noticed that the Data rate is almost the double. In the two others the Modulation technique was the lowest. At the same time it can be observed that QPSK 1/2 was achieved for Downlink in one of the measurements.

The last measurement taken in December is the worst of them. The Data Rate is the same than the first one but it can be seen that all the values about SNR and RSSI are worse in this last case.

Comparing the results from December and those from May it can be easily noticed that weather conditions affect the Network throughput as well as in the previous Area. By observing all the values, it can be seen that the second measurement in December is almost equal than in May according to SNR and RSSI values. However achieved Modulation techniques are quite worse and as consequence the Data rate is affected.

Point Area 3

This is the last Area where it was possible to get in the WiMAX Network. Even when it is further than Area 4 it was possible to get signal because there is a hill used for multiple antennas for different targets. This hill can be viewed from the roof of electrical faculty, where the Base Station is placed. Thus, there was direct line of sight between Base Station and Subscriber Station. The distance between both antennas was around 9.1 Km.

Table 5.3 Measurements results for Area 3

SNR UL (dB)	SNR DL (dB)	RSSI UL (dBm)	RSSI DL (dBm)	Modulation UL	Modulation DL	Data Rate (Kbps)
5,6	12	-98,1	-91	BPSK 1/2	QPSK 1/2	870
5,6	12	-98,3	-91	BPSK 1/2	BPSK 3/4	870
10,7	***16,75***	***-92,6***	***85,75***	***QAM-16 1/2 - BPSK 1/2***	***QAM-64 2/3 - QPSK 3/4***	***3500***

In this last case both measures are almost the same. With a lonely difference, they achieved different Modulation technique for Downlink; QPSK 1/2 and BPSK 3/4. However this difference does not influence in the Data Rate because only the Uplink is used.

This is the case where there is more difference between December and May measurements. This is likely due to the long distance between Base and Subscriber Station, around 9km. All the values are higher and as consequence a better performance of the Network is achieved.

6. CONCLUSIONS and FUTURE WORK

Conclusions are difficult to obtain since there are not equipments for Mobile WiMAX yet. Anyway, some conclusions are already evident without performing Mobile WiMAX equipment.

The main difference in the Physical Layer between Mobile and Fixed WiMAX is related with the multiplexing technique; OFDM comparing with OFDMA. By operating with OFDMA multiplexing technique the Network can perform in a more flexible way for different users. At the same time the Frequency resource is utilized in a more efficient manner.

The new features for Mobility will provide to WiMAX a wider spread in the used Wireless Technologies. This new characteristic, Mobility, is very important because in the last years Fixed WiMAX has already been produced and installed somewhere but less than what it was expected. WiMAX should find the place between WiFi and GSM.

Another conclusion that it can be clearly acquired in that weather influences extremely in the WiMAX Links. It is logical to notice that as long is the link as higher is the weather's influence. It should be possible to ensure a minimum throughput for an internet connection. The maximum coverage is something interesting for studying but the Network provider, the one which is installing the WiMAX Base and Subscriber Stations, should guarantee a minimum bandwidth for each user. This would be impossible if several Antennas are not placed.

At the same time, as weather's influence, building's influence should be inquired. Although it is very troublesome to get a clear idea about this influence since there are a lot of aspects which would affect in the results and most of the cases, especially in Istanbul, each building is different with the building behind. This last comment is supported by the taken measurements since the three Areas were not same far away from the Base Station, but the point whose Data Rate was lowest was not the furthest one.

For the last point it must be noticed that the difference between this two distinctive central frequencies 3.5GHz and 2.3 GHz, deduce that the second one would be properly chosen.

The possible future work is quite clear; some measurements should be taken with Mobile WiMAX equipments. These measurements should be compared with the others taken with Fixed WiMAX equipments and at the same time it would be also interesting to calculate theoretically the maximum throughput of 802.16-2004 Standard, that, by the way, it has been already realized by other Universities. Then, all of these results shall provide a better idea about the most suitable Standard to use in each situation.

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